Long-Term Performance Assessment of Micropiles Subject to Cyclic Axial Loading

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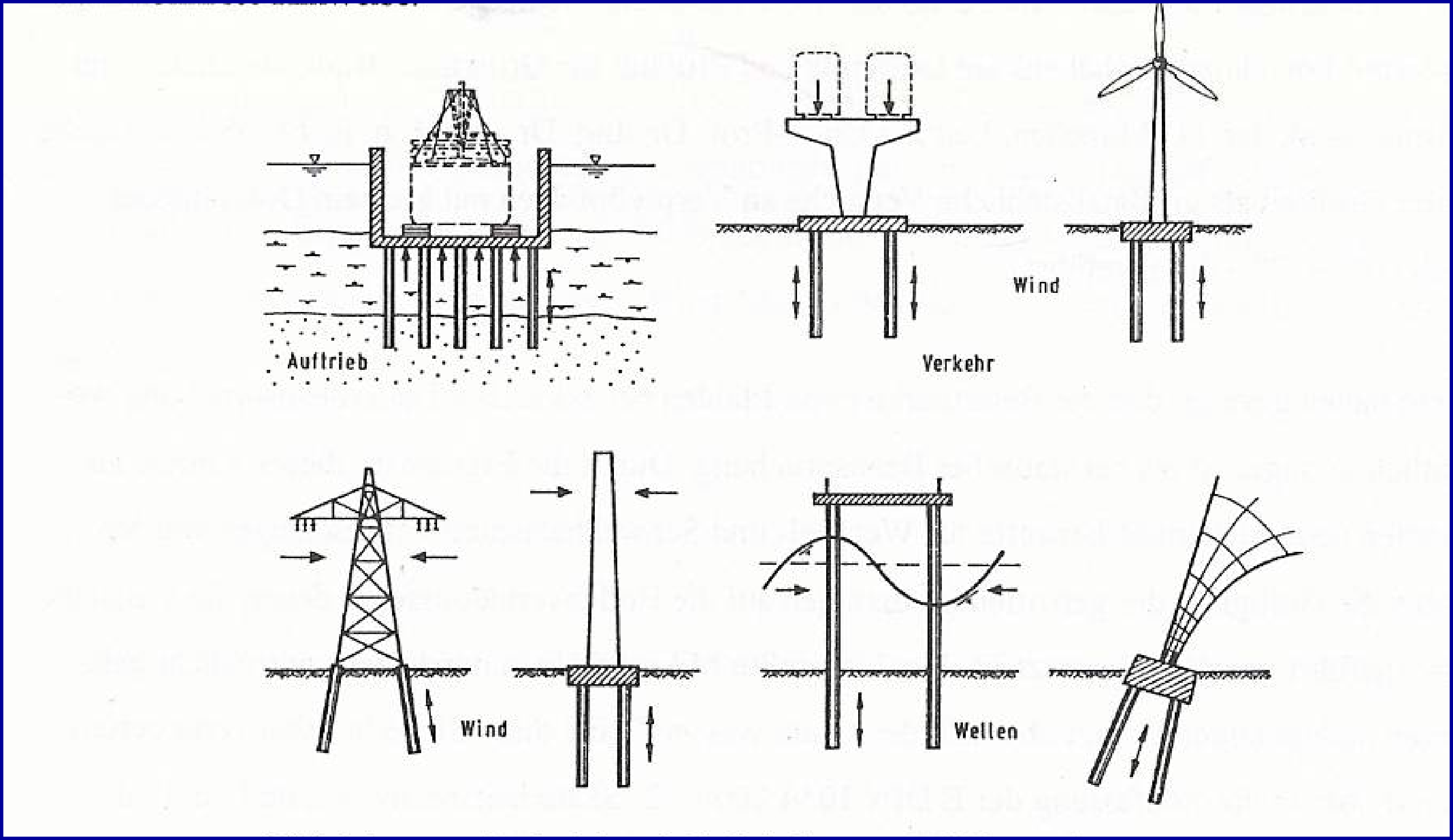
Summary

1. Introduction to Axial Cyclic Behavior of Micropiles
2. Assessment of Current Design & Testing Practice
3. Research Objectives
4. Scope of Research
   - Modeling the long-term behavior of strain-rate and frequency-dependent materials
   - Development of strain-rate controlled testing procedure to assess long-term strain under:
     - Monotonic axial loading
     - Cyclic axial loading
   - Experimental model evaluation
     - * Monotonic & cyclic axial loading tests on plastic samples
     - Monotonic & cyclic calibration chamber micropile model testing
5. Conclusions & Research Needs

Axial Cyclic Behavior of Piles: Applications

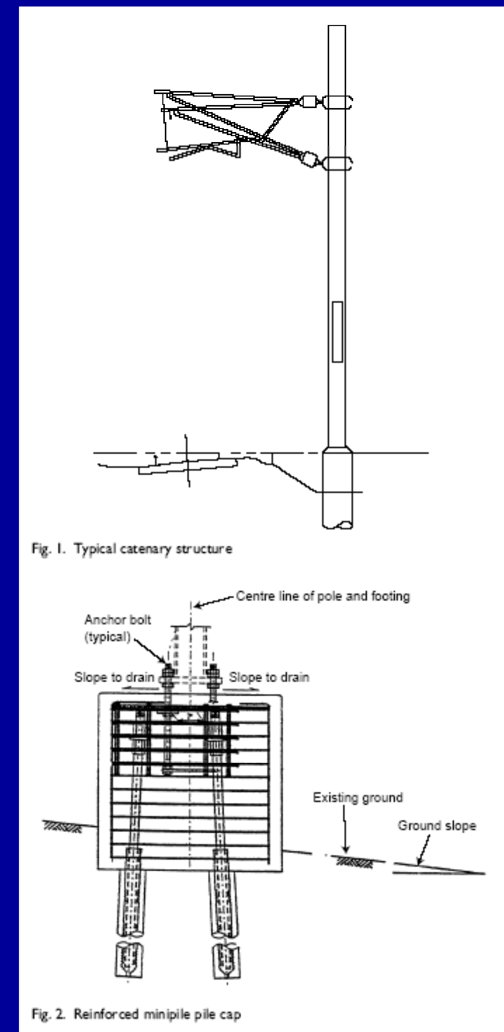


Examples of Cyclically Loaded Pile Foundations (Schwarz, 2002)

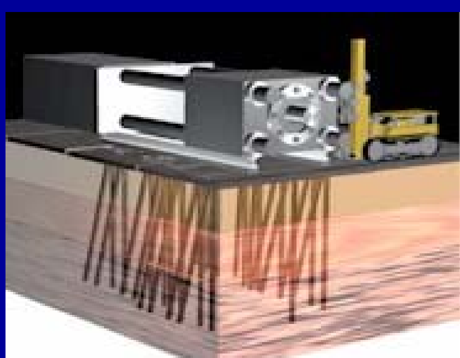
Axial Cyclic Behavior of Micropiles: Testing Practice

Unique applications
(Courtesy of United States Navy)

Full-scale field testing (USN, 2000)



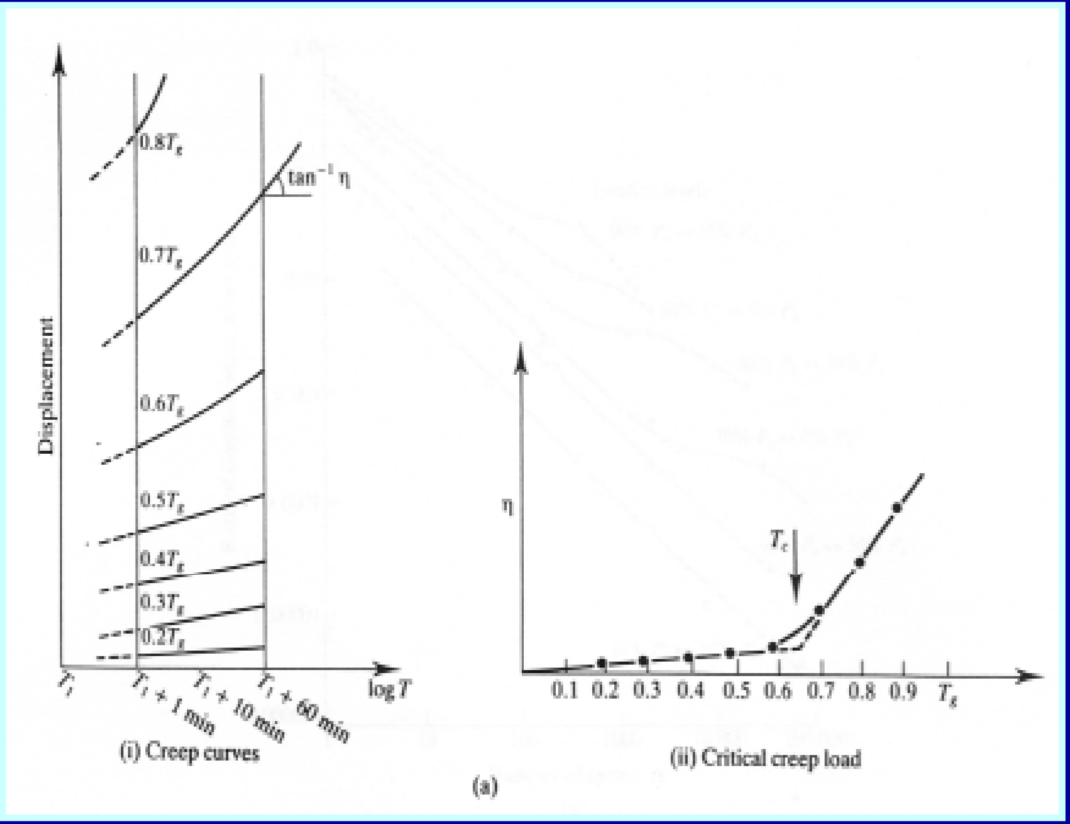
Catenary towers
(Cavey et al., 2000)



Machine foundations
(Cadden et al., 1998)

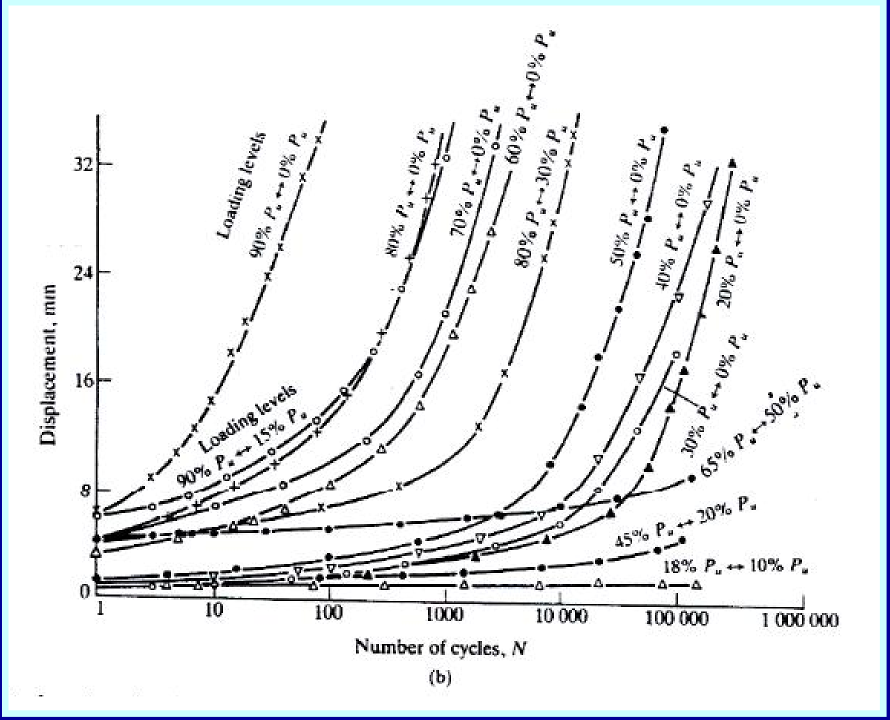
Full-scale field testing (Fujita Corp.)

Axial Creep Load Testing : Design & Testing Practice

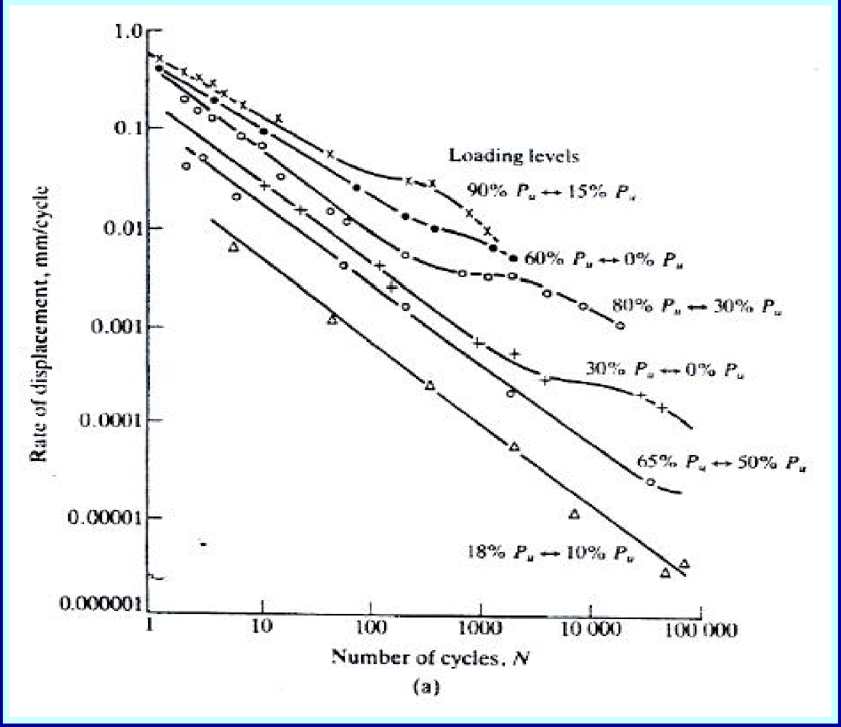


Anchor tension test for determination of critical creep load (Bureau Securitas, 1977)

Axial Cyclic Load Testing of Ground Anchors: Field Observations



The effect of number of load cycles on anchor displacement for a range of load amplitudes (After Al-Mosawe, 1979)



The effect of load cycles on the rate of anchor displacement (After Al-Mosawe, 1979)

Limitations of Practice

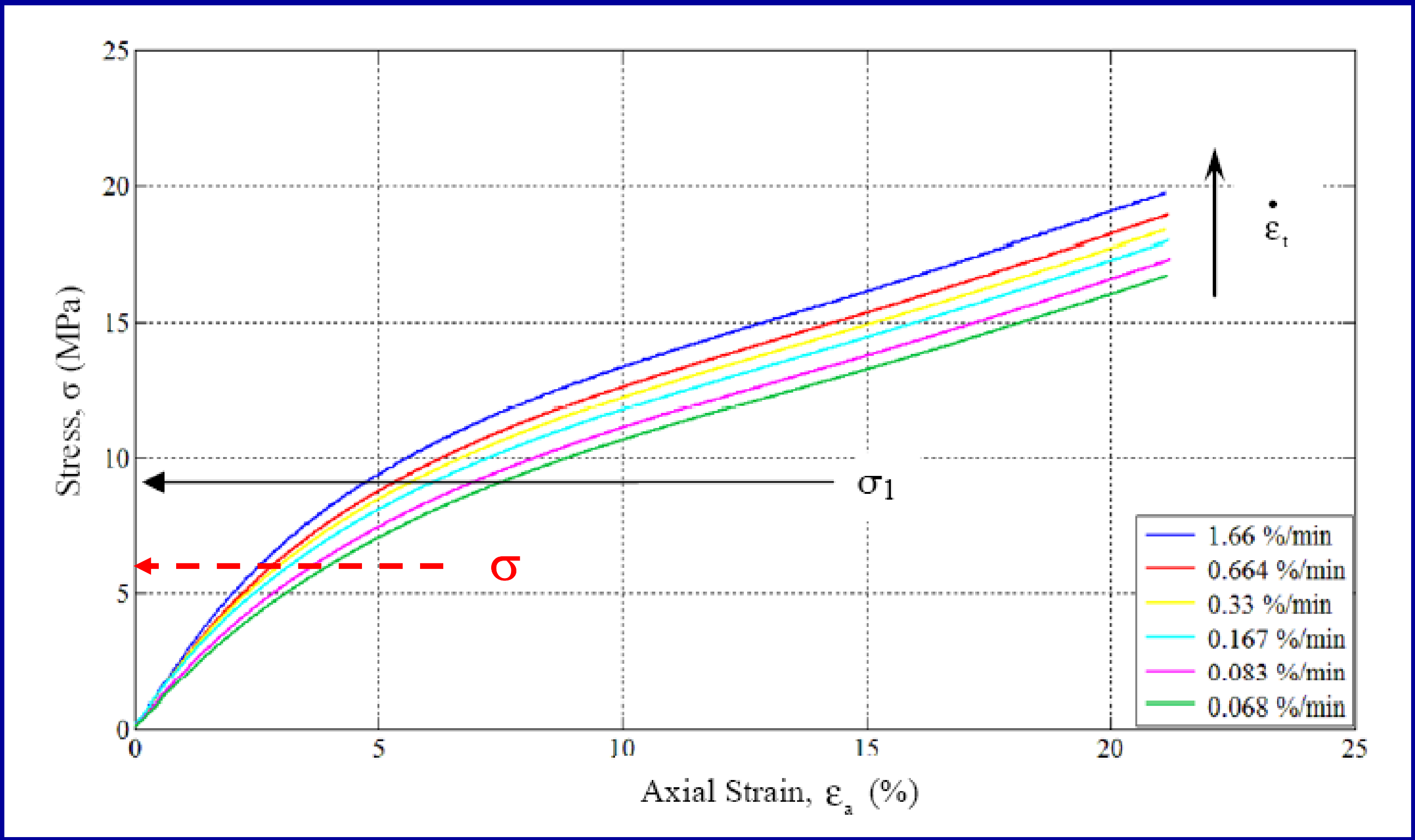
- Ground anchors, micropiles, piles, & drilled shafts
  - Creep – Extrapolating short-term, load-control test results for prediction of long-term strain.
  - Cyclic loading – Extrapolating results of load-control tests with limited number of cycles to predict long-term cyclic strain OR long-term load-control cyclic testing leading to costly, time-consuming & impractical testing procedures.

Research Objectives

1. Develop for strain-rate dependent or frequency dependent materials a strain-rate controlled testing procedure and interpretation model for using short-term test results to:
   - Predict long-term strain under monotonic and cyclic axial loading
   - Establish a Critical Creep Load and Critical Cyclic Load under monotonic and cyclic axial loading, respectively.

2. Experimentally evaluate the testing procedure and the interpretation model through the performance of monotonic and cyclic strain-rate controlled and load-controlled tests including:
   - * Axial loading tests on plastic samples
   - Calibration chamber tests on model micropiles.

Strain-Rate Controlled Axial Compression Tests



Load Control:

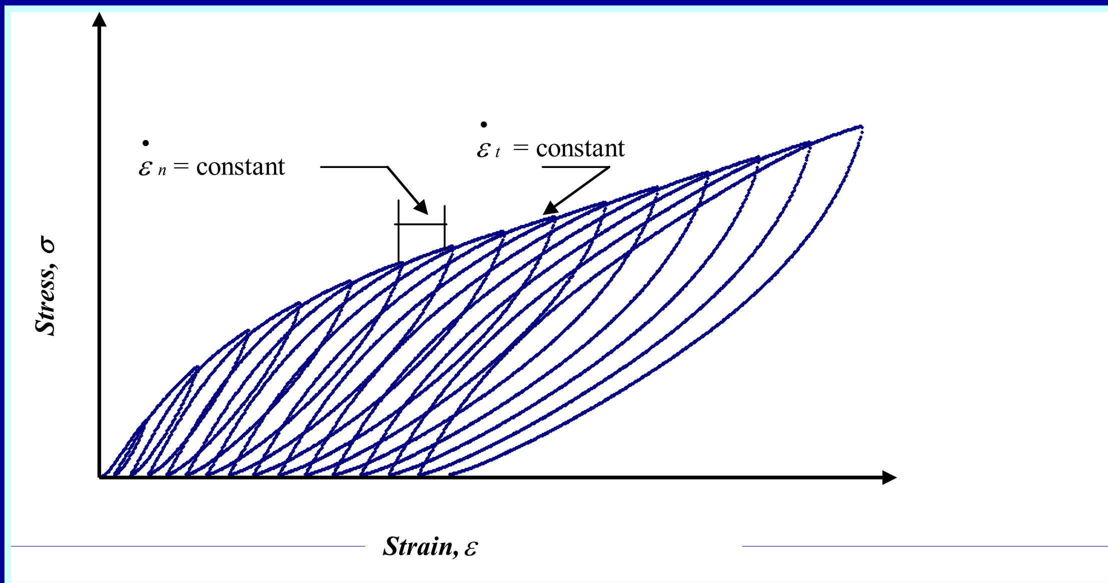
$$\varepsilon = f(t,\sigma)$$

Strain Rate Control:

$$\varepsilon = g(\dot{\varepsilon}_t,\sigma)$$

Strain rate controlled monotonic axial compression tests results

Strain-Rate Controlled Cyclic Testing Procedure



Conceptual strain-rate controlled cyclic loading function

Load Control:

$$\varepsilon = f\,(\sigma, \dot{\omega}, t)$$

Strain Rate Control:

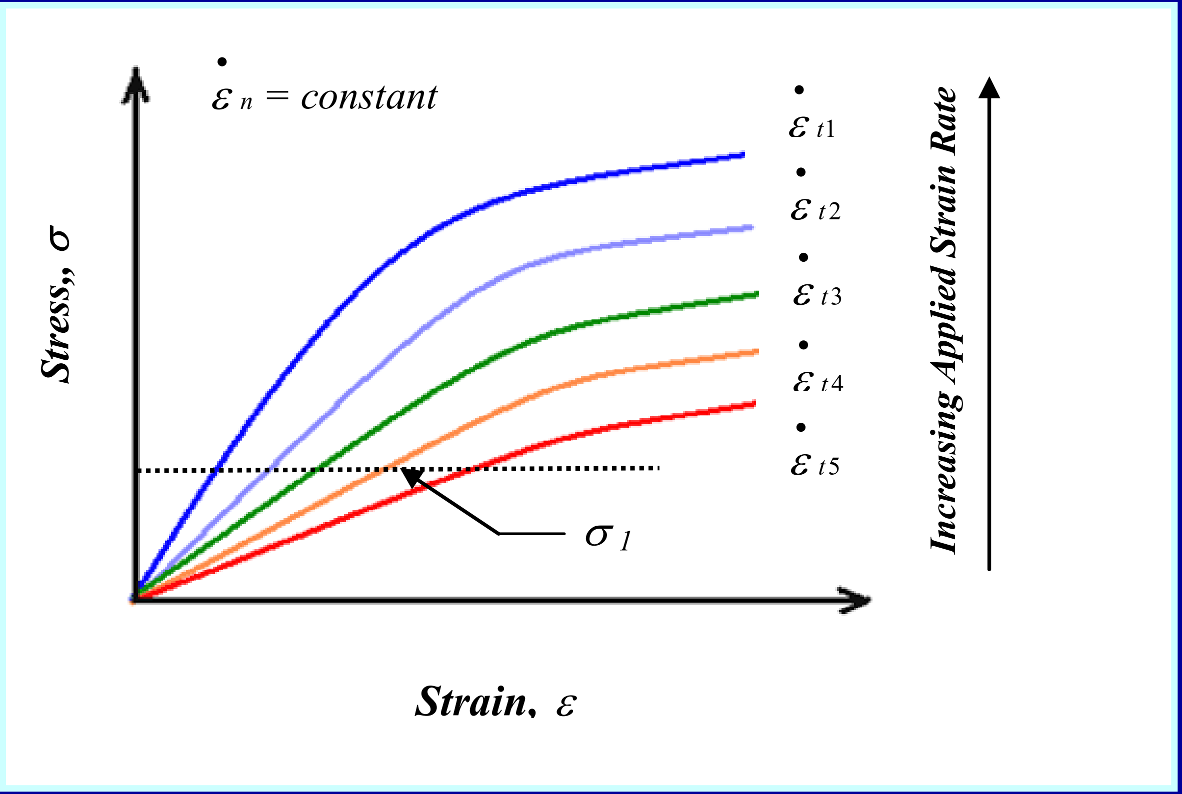
$$\varepsilon = g\,(\dot{\varepsilon}_t, \dot{\varepsilon}_n, \sigma)$$

$$\dot{\omega}_l = \tfrac{1}{2}\,(\dot{\varepsilon}_t / \dot{\varepsilon}_n)$$

$$\dot{\omega}_n = \{1/n\}\,(\dot{\omega}_l)$$

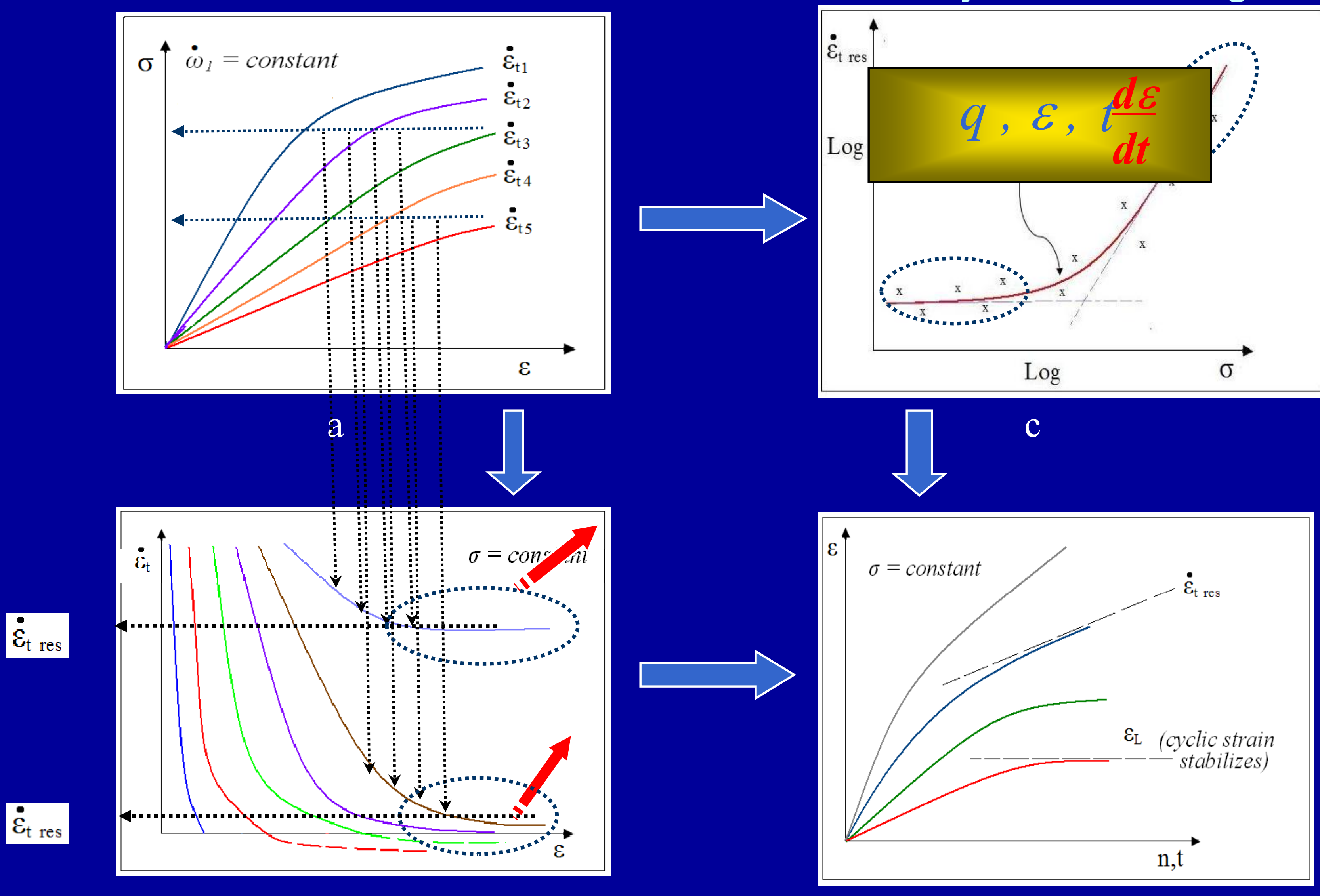
1. *Constant Applied Strain Rate (cyclic strain rate constant)*
2. *Constant Cyclic Strain Rate (applied strain rate constant)*

Model for Cyclic Loading: Applied Strain-Rate Control



Conceptual applied strain-rate controlled cyclic loading response for a series of cyclic loading tests (cyclic envelope shown for clarity)

Model for Strain-Rate Controlled Cyclic Loading



$$\frac{d\varepsilon}{dt} = \dot{\varepsilon} = \dot{\varepsilon}_o * \varepsilon^{-\beta} + \dot{\varepsilon}_{res}$$

$$\varepsilon(t) = [\varepsilon_o (\beta + 1)]^{1/(\beta+1)} \times t^{1/(\beta+1)}$$

The procedure charts including (a) stress, σ, vs. strain, ε, at constant applied strain rate (b) strain rate vs. strain, ε at constant stress (c) residual strain rate vs. stress, σ and (d) strain, ε, vs. cycle number, n at constant stress

Polytechnic Institute of NYU

Urban Infrastructure Institute

Experimental Research Program : Phase 1

Instron 8800 servo-hydraulic fatigue testing system

Low-density polyethylene plastic rod

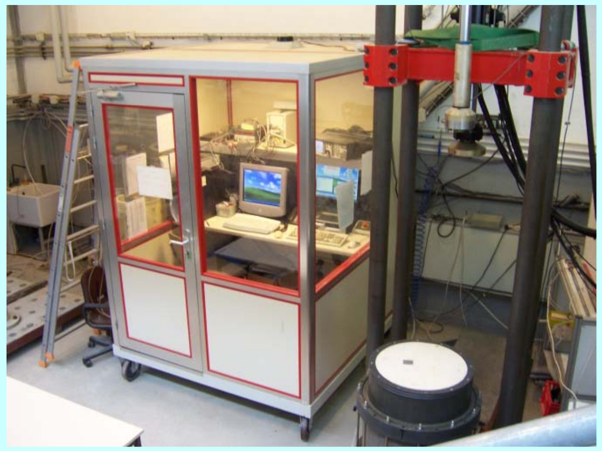
Ecole Nationale des Ponts et Chaussées

CERMES

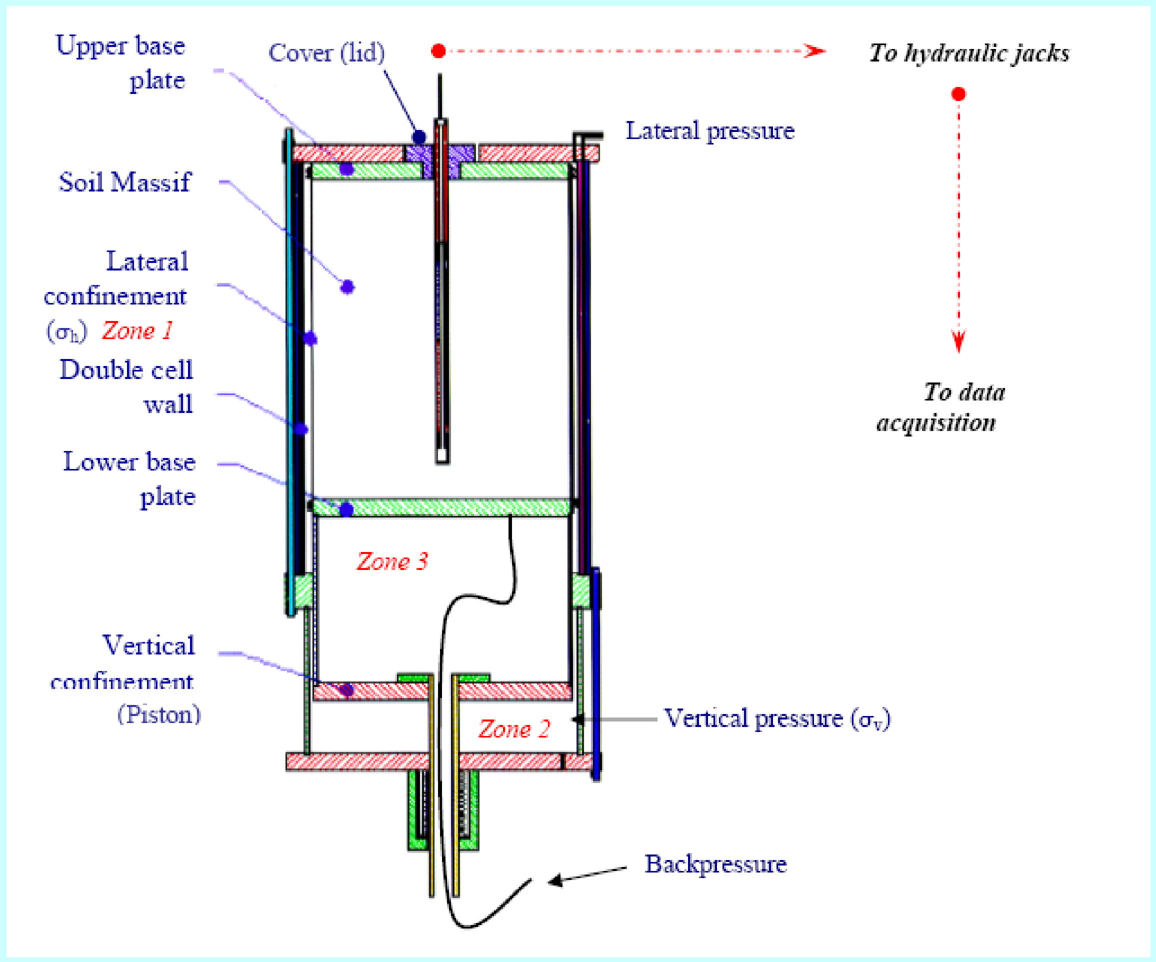
Centre d'Enseignement et de Recherche en Mécanique des Sols

Experimental Research Program : Phase 2

CERMES Calibration Chamber

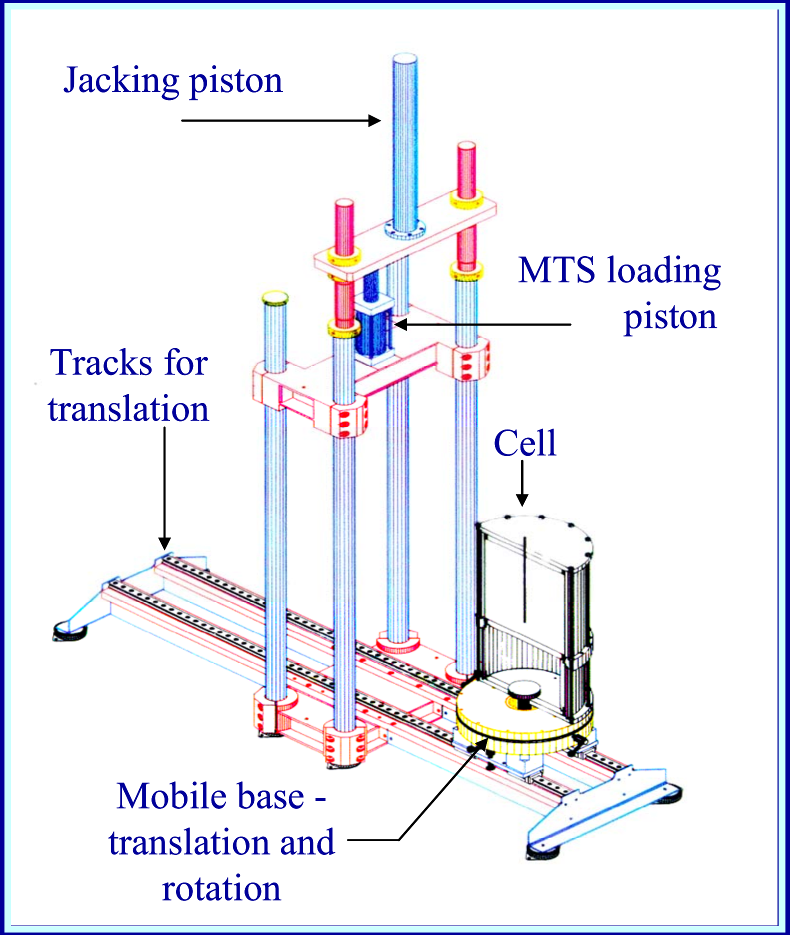


Data Acquisition & Command Control Center

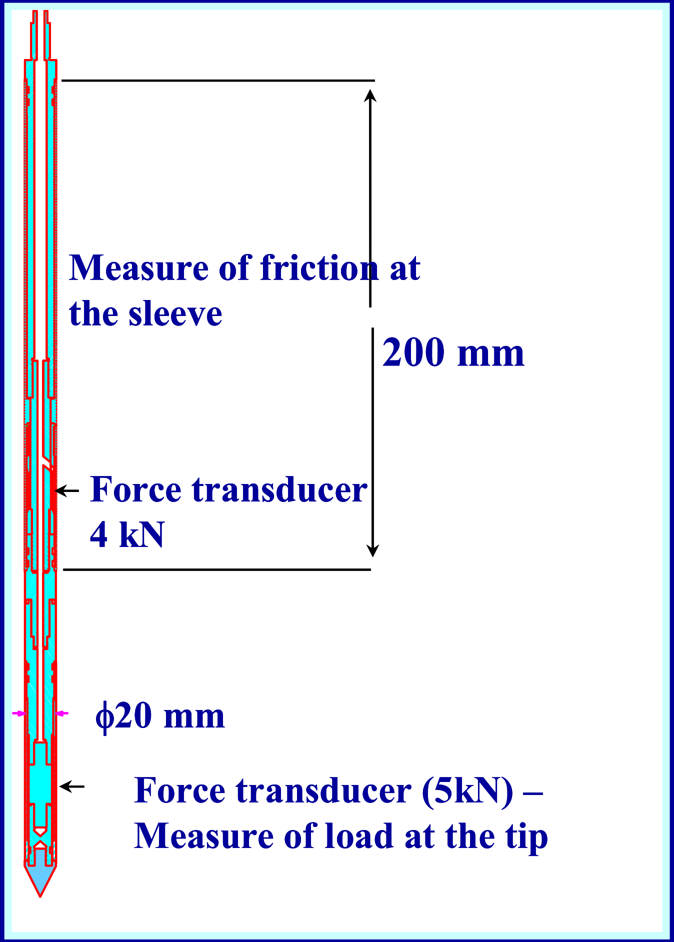


Principle Schematic of the CERMES Calibration Chamber

Experimental Equipment

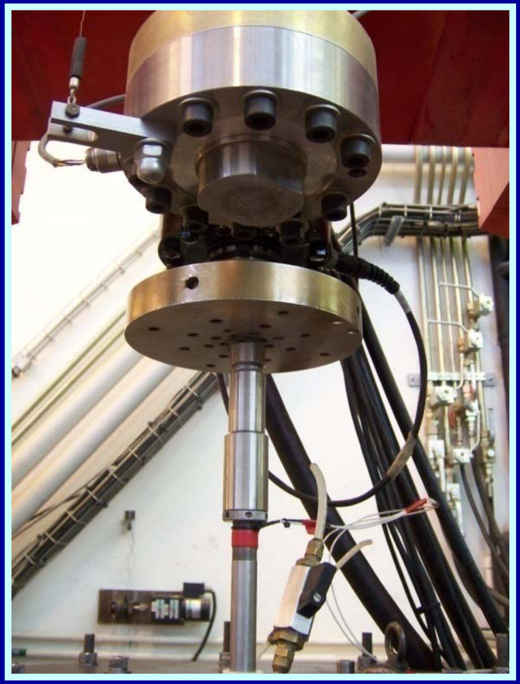


Schematic of the jacking and loading system



Model micropile

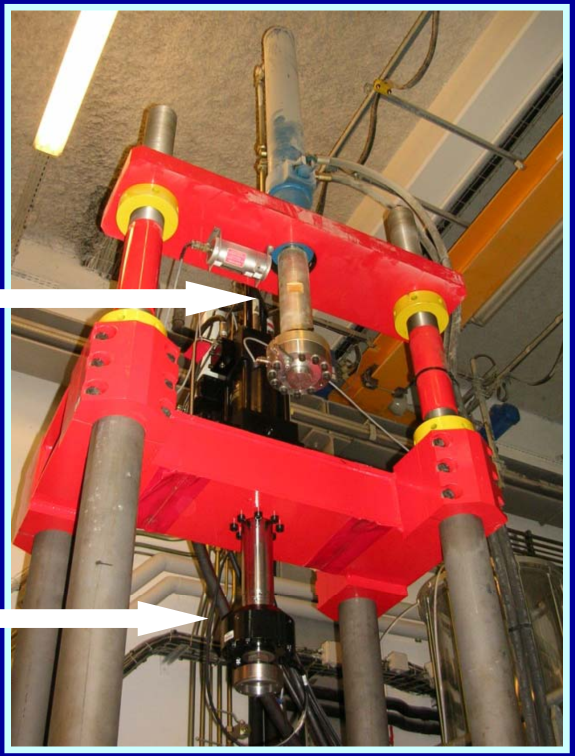
Jacking & Loading

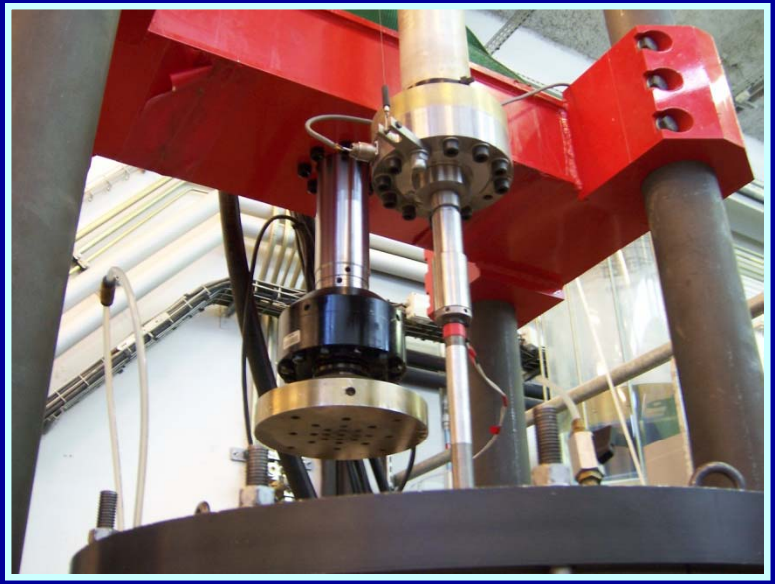


Loading of micropile

Hydraulic jack
Single stroke
(force transducer)

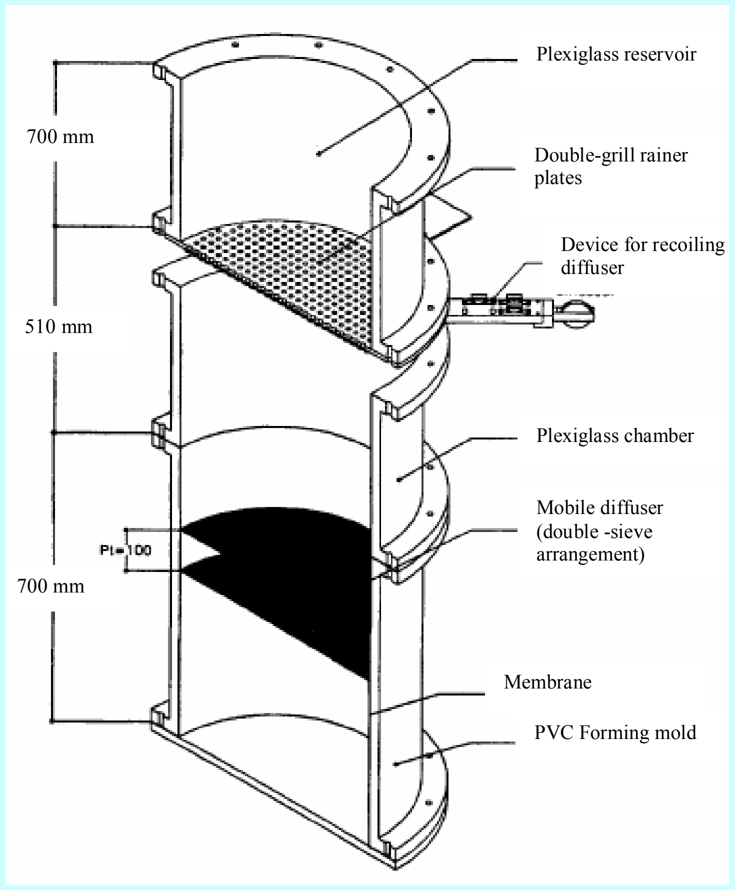
Loading jack
(Displacement & force
transducer at head)



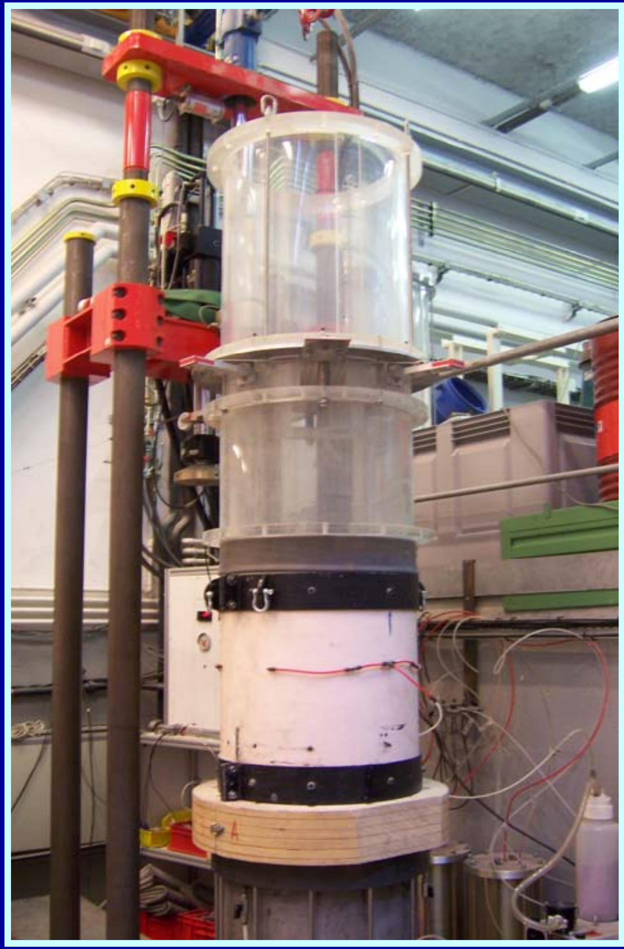


Jacking of micropile

Experimental Equipment

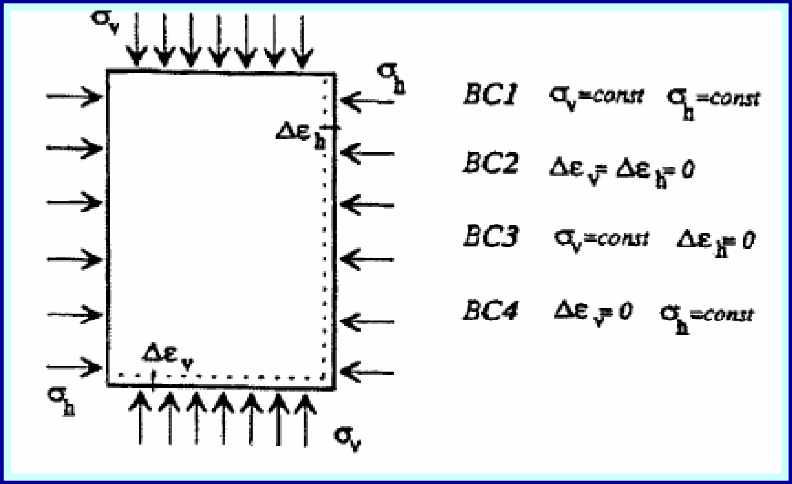


Section through pluviation device (Dupla, 1995)



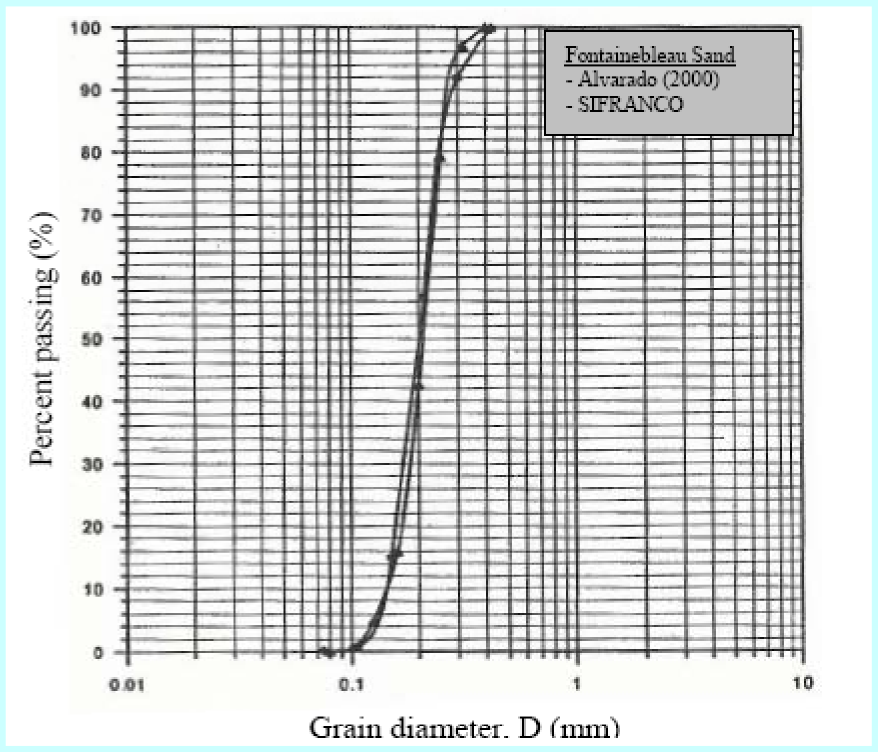
Pluviation system

Applied Stresses



Boundary conditions
(after Balachowski, 1995)

Fontainebleau Sand : Material Parameters



Grain-size distribution curve

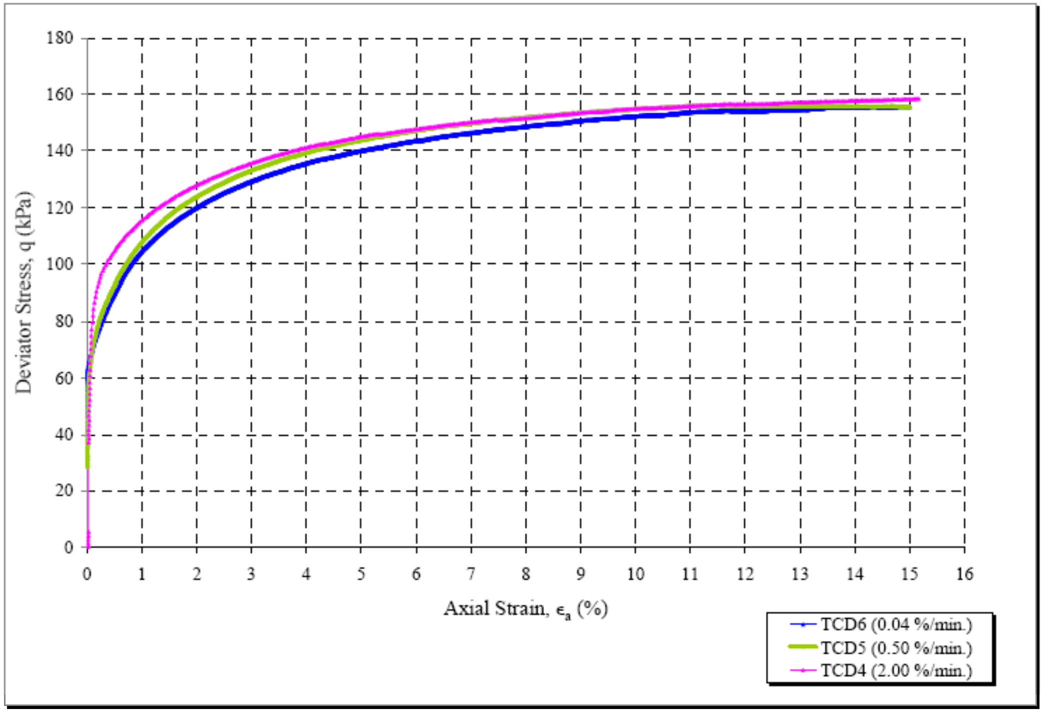
Test	Designation	M_s (Kg)	$I (g/cm^2/s)$	I_D
1	MDRC-0	225.33	2.71	0.401
2	MDRC-1	225.38	2.72	0.405
3	MDRC-1b	224.96	2.71	0.396
4	MDRC-1c	224.06	2.70	0.378
5	MDRC-3	221.92	2.67	0.335
6	MDRC-3a	222.96	2.69	0.356
7	MDRC-3b	224.38	2.70	0.385
8	CDRC-1	223.96	2.70	0.376
9	CDRC-2	224.56	2.70	0.388
10	CDRC-3	224.24	2.70	0.382
11	CDRC-3a	223.90	2.70	0.375
12	FDRC-1	223.94	2.70	0.376
13	FDRC-2	225.54	2.72	0.408
14	FDRC-2a	223.96	2.70	0.376
15	FDRC-3	224.22	2.70	0.382
16	FDRC-4	224.64	2.71	0.390
17	FDRC-5	225.82	2.72	0.414
18	FDRC-6	225.72	2.72	0.412
19	FDRC-8	225.83	2.72	0.414
20	FLC-1	225.52	2.72	0.408
21	FLC-2	225.00	2.71	0.397

Test massif characteristics

Sand	D_{50} (mm)	e_{max}	e_{min}	ρ_s (g/cm^3)	ρ_d (g/cm^3)	ρ_{dmax} (g/cm^3)
AF	0.21	0.94	0.54	2.65	1.37	1.72

Characteristics of Fontainebleau sand

Experimental Research Program : Phase 2



Drained triaxial compression tests on Fontainebleau sand : Effect of axial strain rate

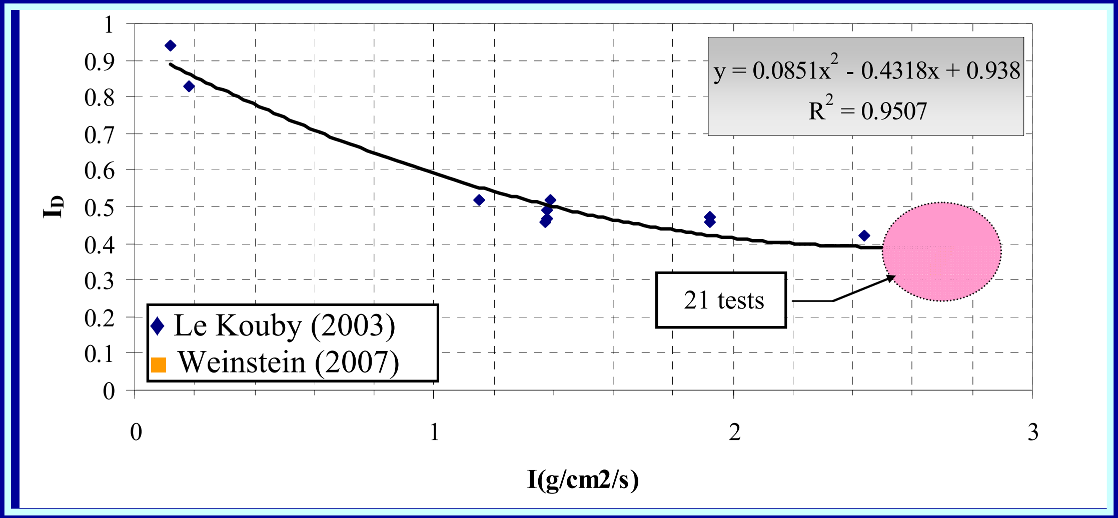
Bishop & Wesley triaxial cell and Fontainebleau soil specimen after test (TCD6, σ_c = 100 kPa)

Experimental Research Program : Phase 2

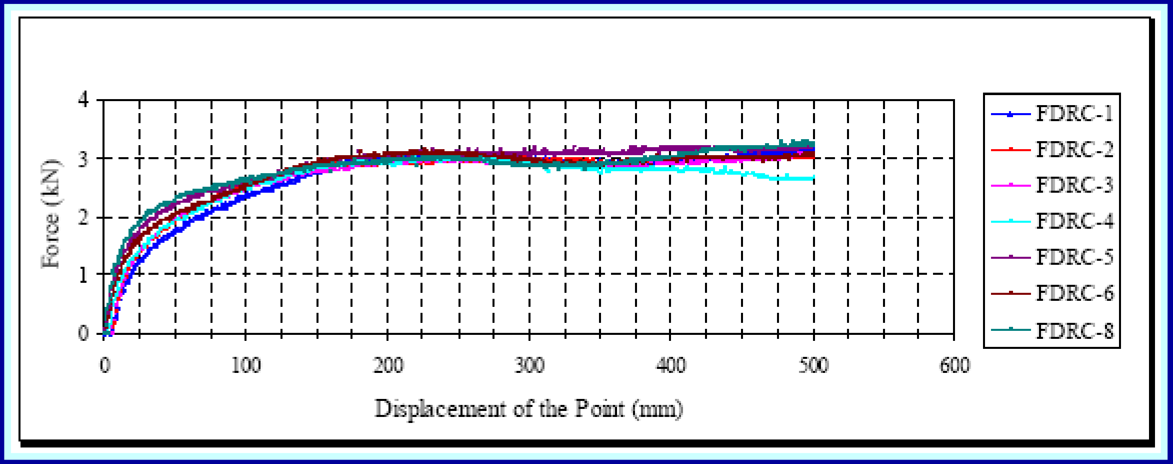
Test	Massif	I_D	K_0	$\dot{\delta}_t$ (mm/min)	$\dot{\delta}_n$ (mm/cycle)	$\dot{\omega}_1$ (cycle/min)
MDRC-0	1	0.385	0.40	1/0.1/0.01	na	na
MDRC-1	2	0.405	0.40	1	na	na
MDRC-1b	2	0.396	0.40	1	na	na
MDRC-1c	3	0.378	0.40	1	na	na
MDRC-3	3	0.335	0.40	0.02	na	na
MDRC-3a	4	0.356	0.40	0.02	na	na
MDRC-3b	4	0.385	0.40	0.02	na	na
CDRC-1	5	0.376	0.40	1	0.2	5
CDRC-2	6	0.388	0.40	0.25	0.05	5
CDRC-3	7	0.382	0.40	0.02	0.004	5
CDRC-3a	8	0.375	0.40	0.02	0.004	5
FDRC-1	5	0.376	0.40	1	1	1
FDRC-2	6	0.408	0.40	1	0.1	10
FDRC-2a	8	0.376	0.40	1	0.1	10
FDRC-3	7	0.382	0.40	1	0.02	50
FDRC-4	8	0.390	0.40	1	0.004	250
FDRC-5	9	0.414	0.40	1	0.002	500
FDRC-6	9	0.412	0.40	1	0.001	1000
FDRC-8	7	0.414	0.40	1	0.0004	2500
FLC-1	5	0.408	0.40	1	na	na
FLC-2	6	0.397	0.40	1	na	na

Testing Schedule – Monotonic & cyclic displacement-rate and load controlled tests

Experimental Testing Results (Construction & Jacking): Repeatability

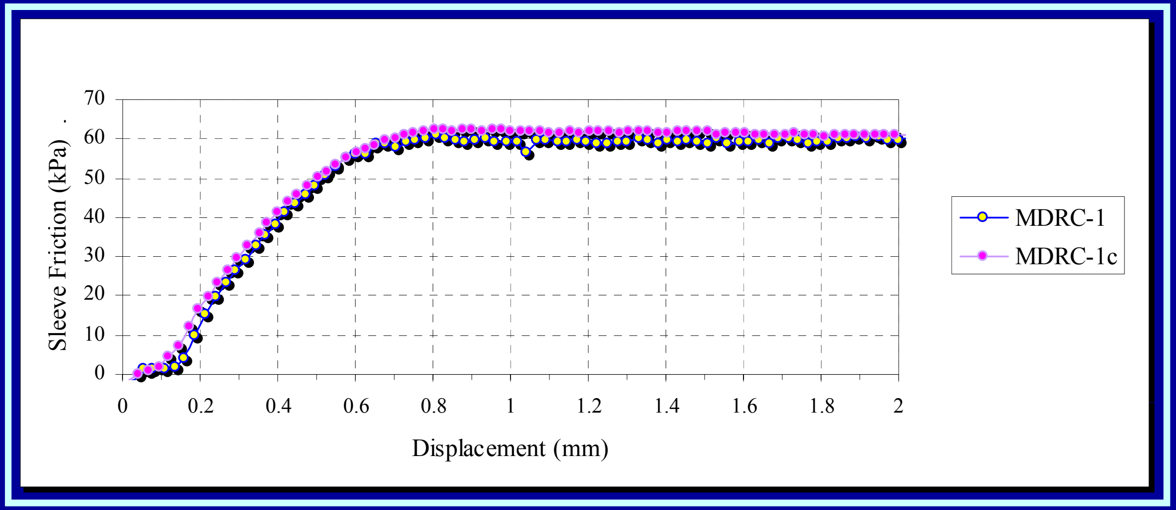


Influence of deposition intensity, I on density index, I_D
(Fontainebleau sand)

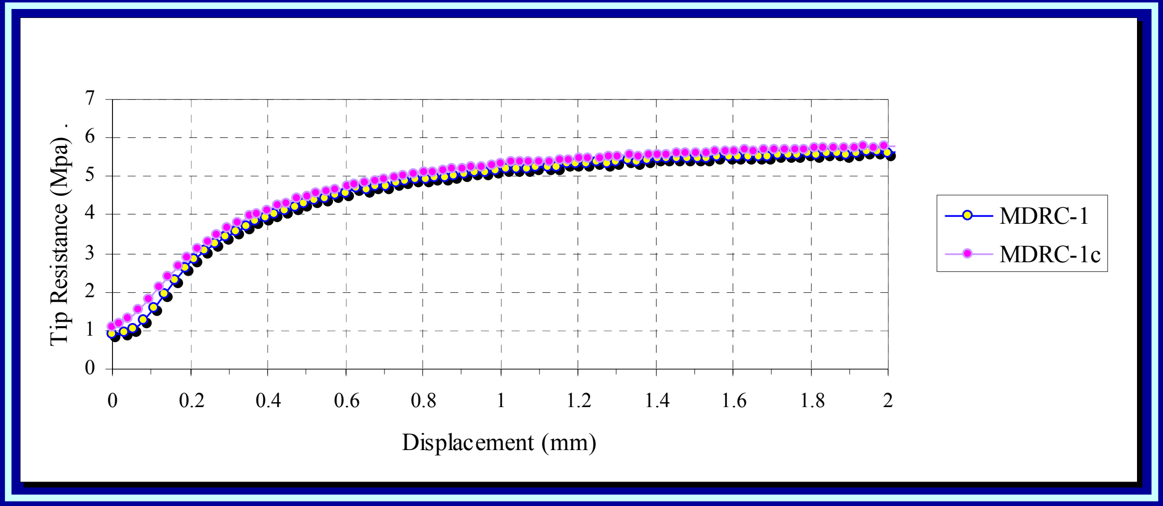


Force versus displacement : Repeatability of jacking phase

Experimental Testing Results (Monotonic Loading): Repeatability

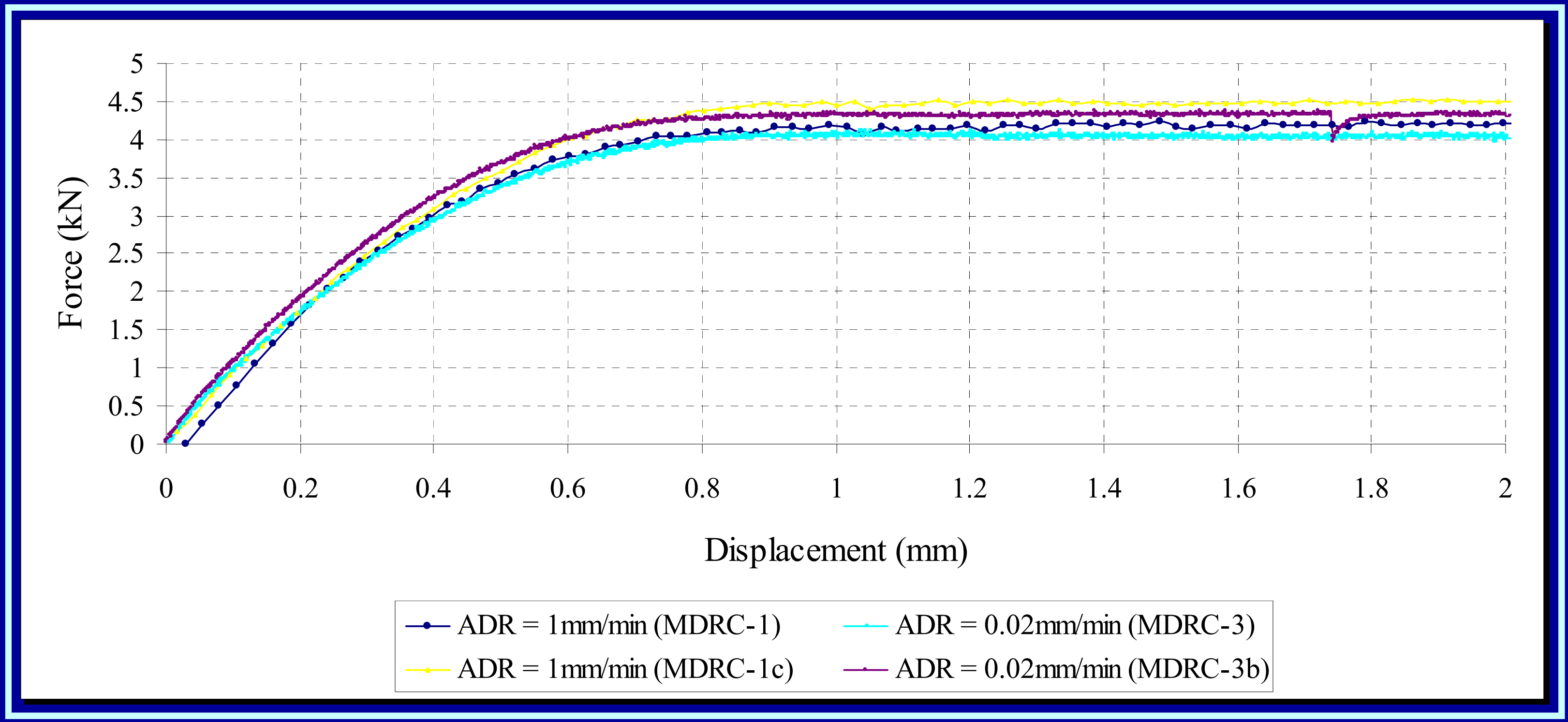


Sleeve friction - displacement curves for two loading rates



Tip resistance - displacement curves for two loading rates

Experimental Testing Results (Monotonic Loading): Repeatability & Influence of Monotonic Displacement Rate



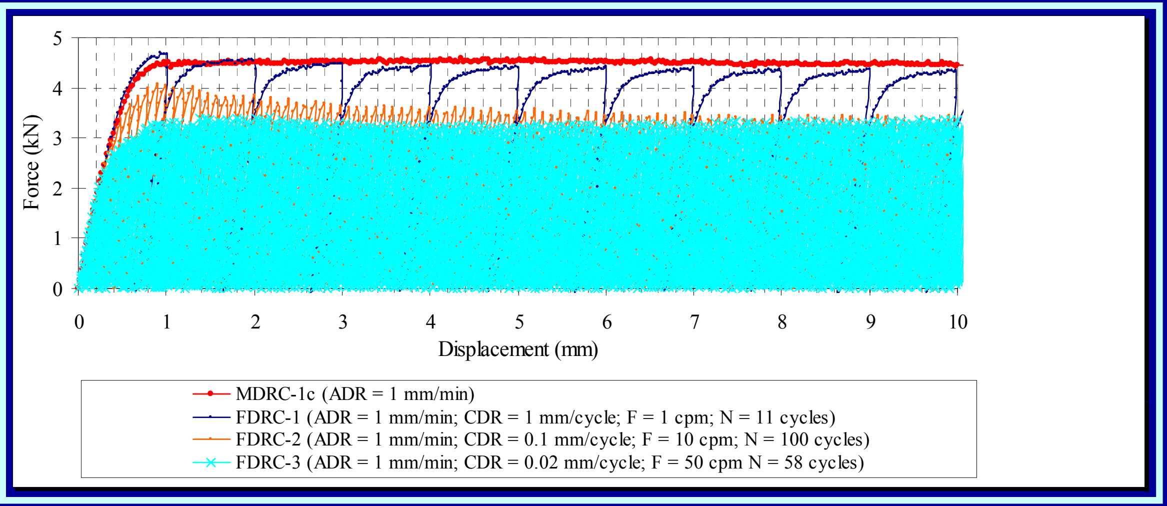
Load-displacement curves for two loading rates (4 tests)

Experimental Evaluation of Testing Procedure & Interpretation Model for Cyclic Loading : (Cyclic Displacement Rate)

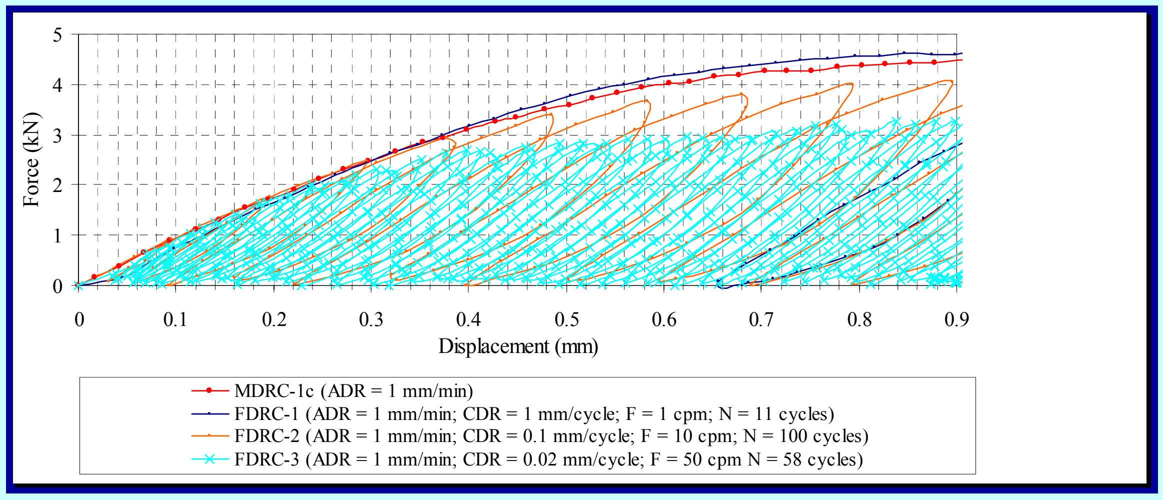
Test Designation	Applied Displacement Rate (mm/min)	Cyclic Displacement Rate (mm/cycle)	Frequency (N =1) (cycle/min)
FDRC-1	1	1	1
FDRC-2	1	0.1	10
FDRC-3	1	0.02	50
FDRC-4	1	0.004	250
FDRC-5	1	0.002	500
FDRC-6	1	0.001	1000
FDRC-8	1	0.0004	2500
FLC-1	1	*n.a.	n.a.
FLC-2	1	n.a.	n.a.

Testing Schedule – Cyclic displacement-rate and load controlled tests

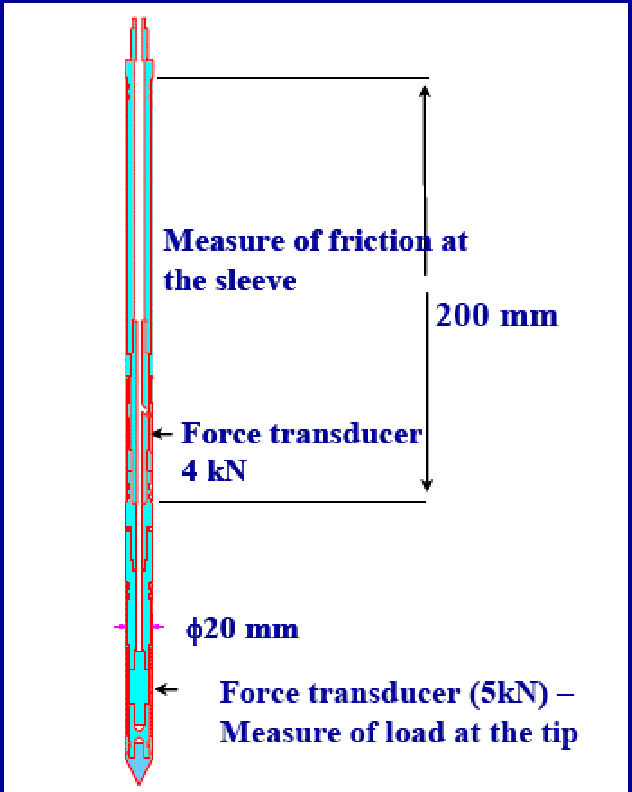
Experimental Testing Results (Cyclic Loading): Influence of Cyclic Displacement Rate



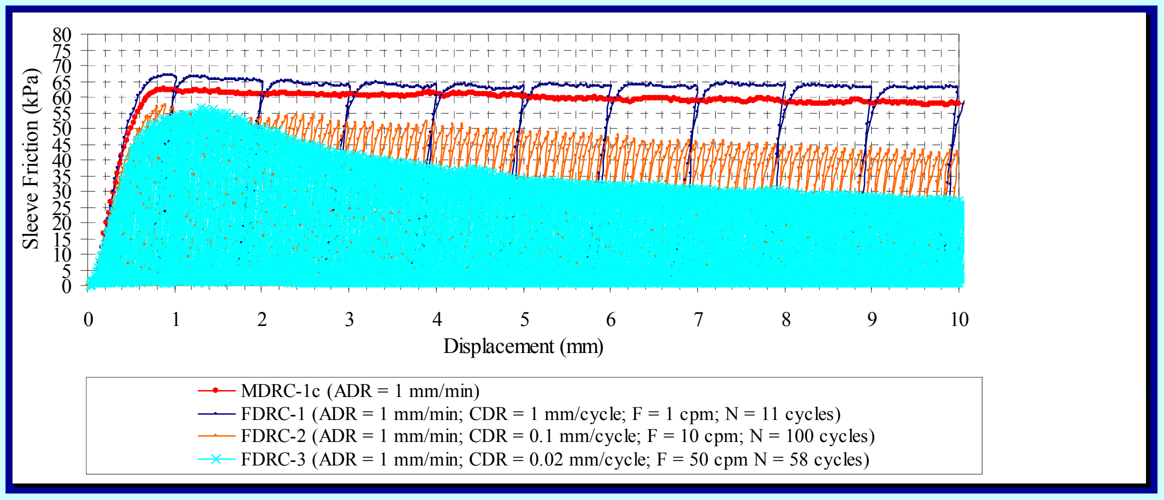
Force vs. displacement



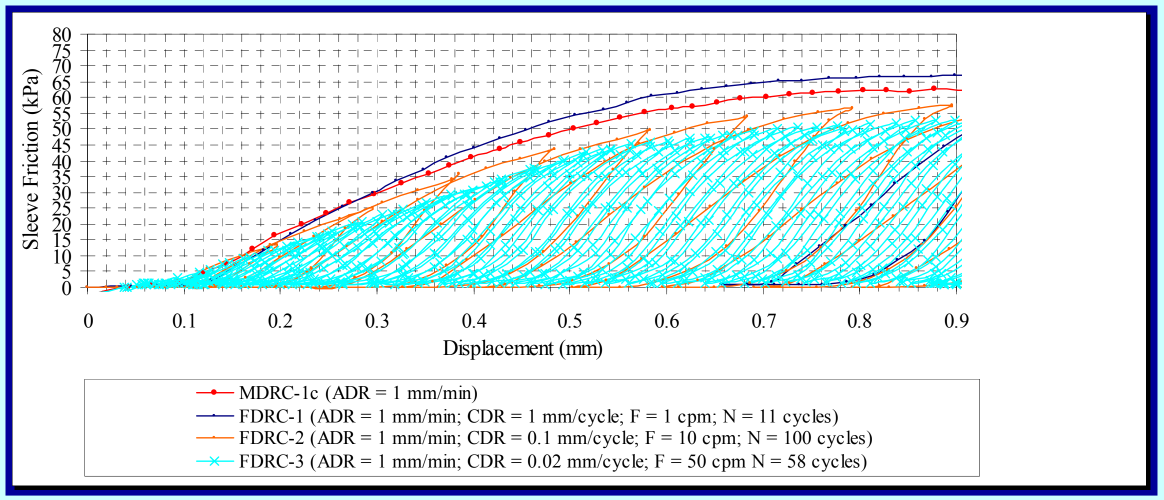
Force vs. displacement – region of initial displacement



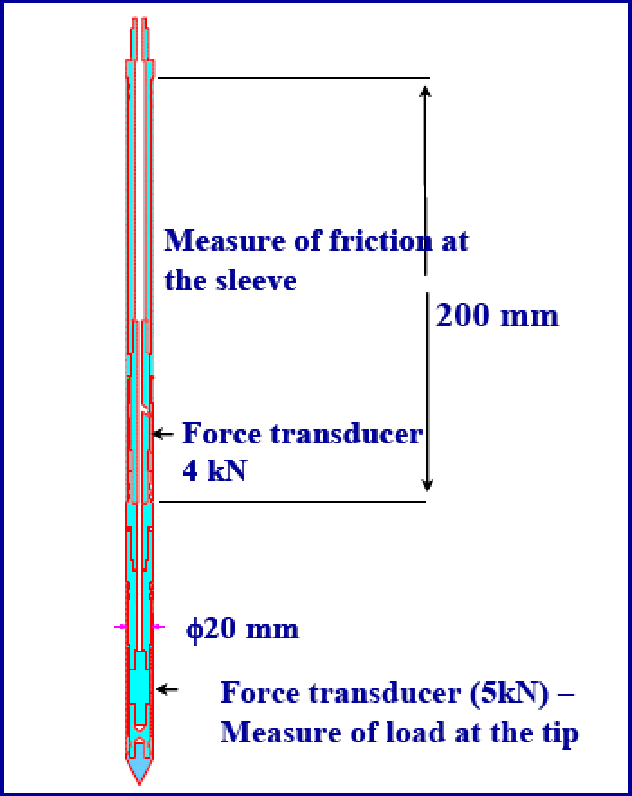
Experimental Testing Results (Cyclic Loading): Influence of Cyclic Displacement Rate



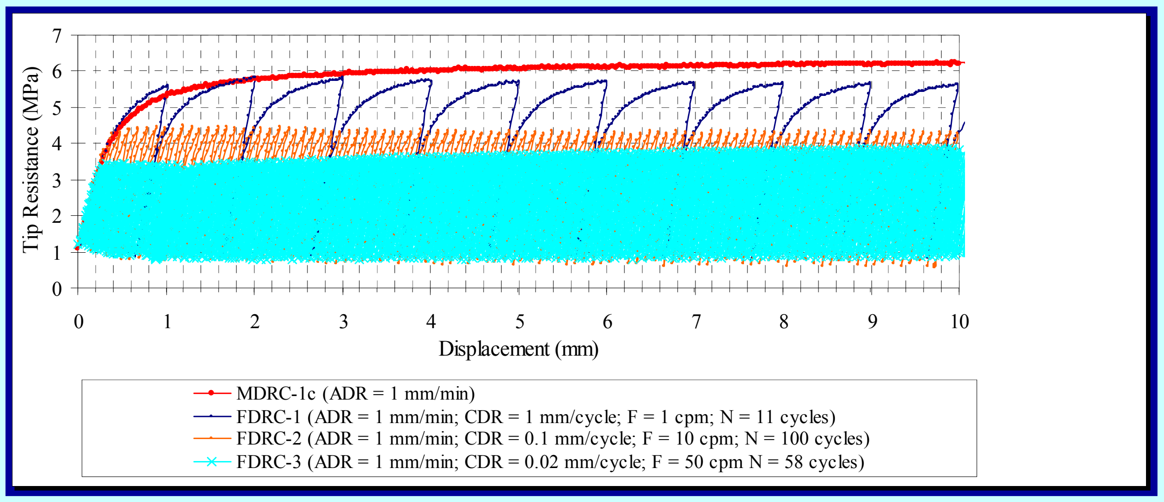
Sleeve friction vs. displacement



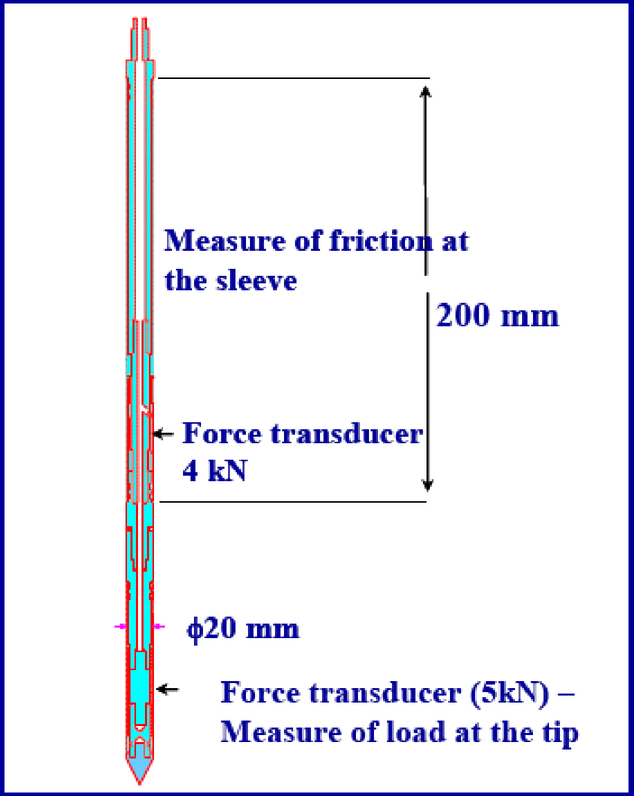
Sleeve friction vs. displacement – region of initial displacement

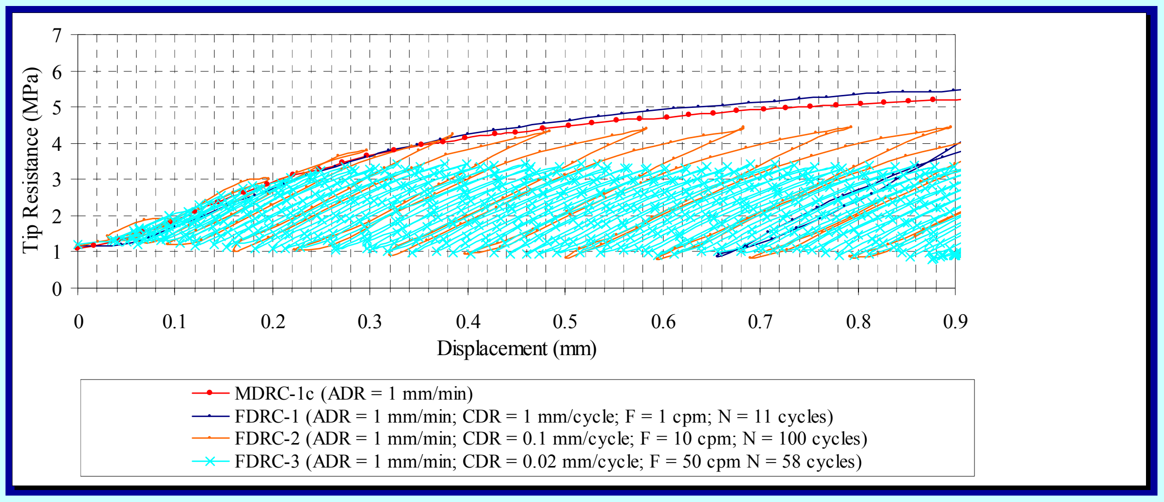


Experimental Testing Results (Cyclic Loading): Influence of Cyclic Displacement Rate



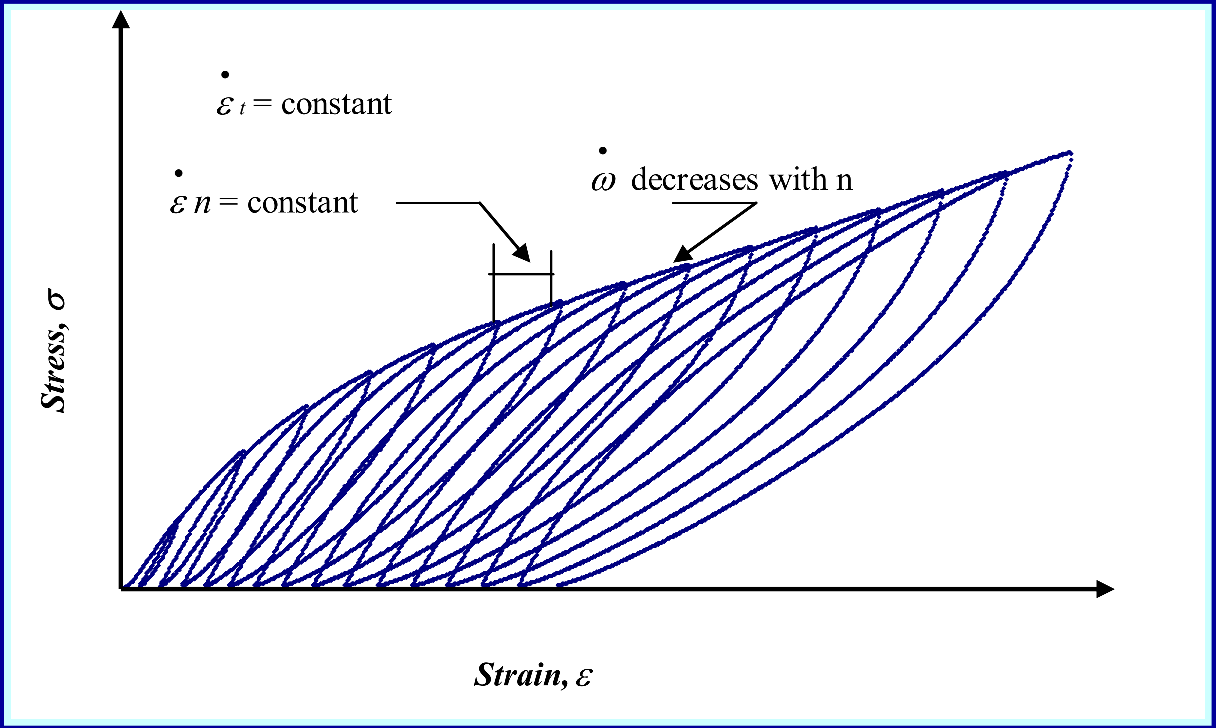
Tip resistance vs. displacement





Tip resistance vs. displacement – region of initial displacement

Model for Cyclic Loading: Cyclic Strain-Rate Control (Frequency-Dependent Material)



Conceptual cyclic strain-rate controlled cyclic loading function

Load Control:

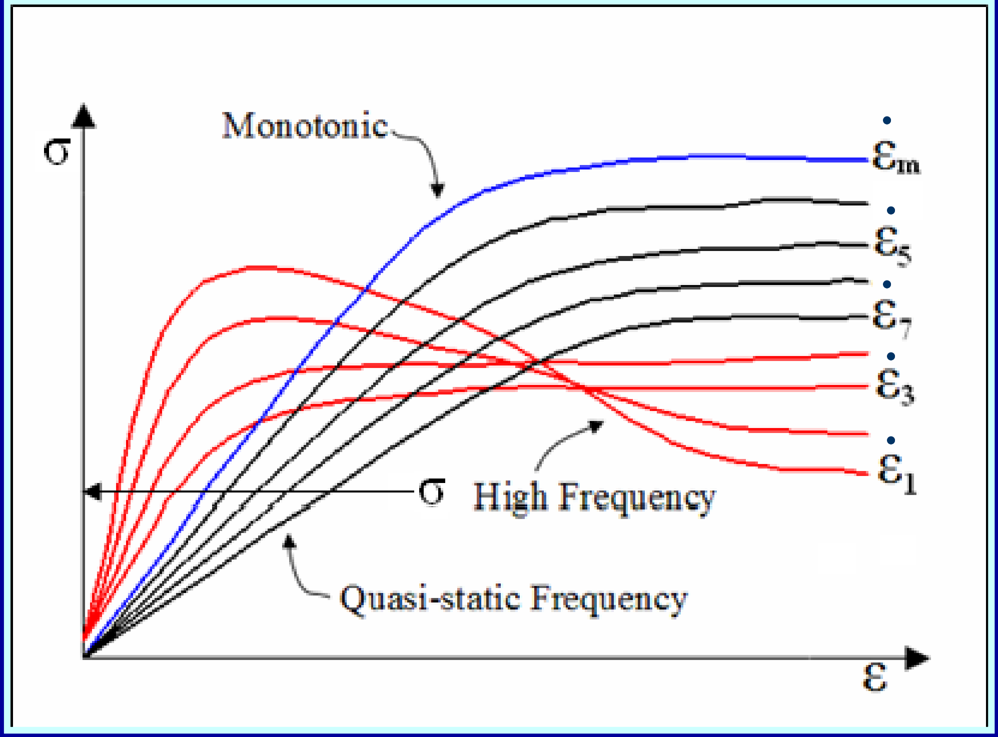
$$\varepsilon = f\,(\sigma, \dot{\omega}, t)$$

Strain Rate Control:

$$\varepsilon = g\,(\dot{\varepsilon}_t, \dot{\varepsilon}_n, \sigma)$$

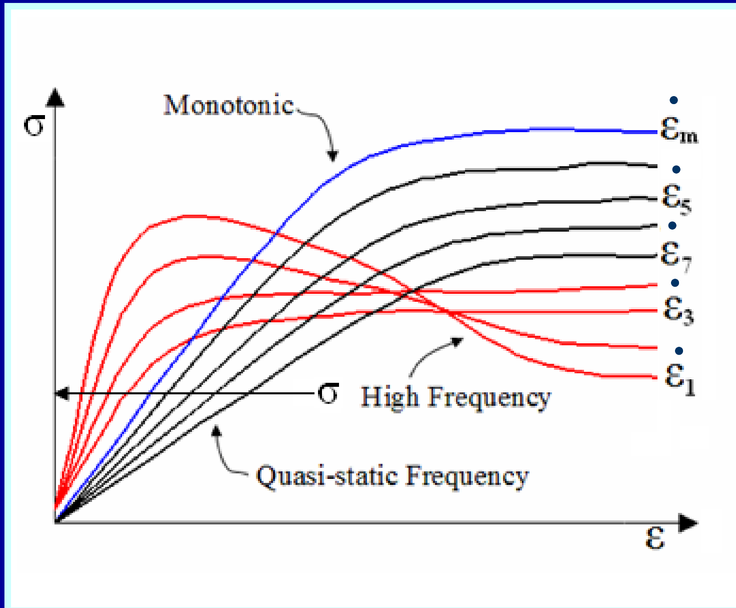
** Constant Cyclic Strain Rate (applied strain rate constant)*

Interpretation Model for Cyclic Loading: Cyclic Strain-Rate Control



Conceptual cyclic strain-rate controlled cyclic loading response for a series of cyclic loading tests (cyclic envelope shown for clarity)

Model for Cyclic Loading: Cyclic Strain-Rate Control



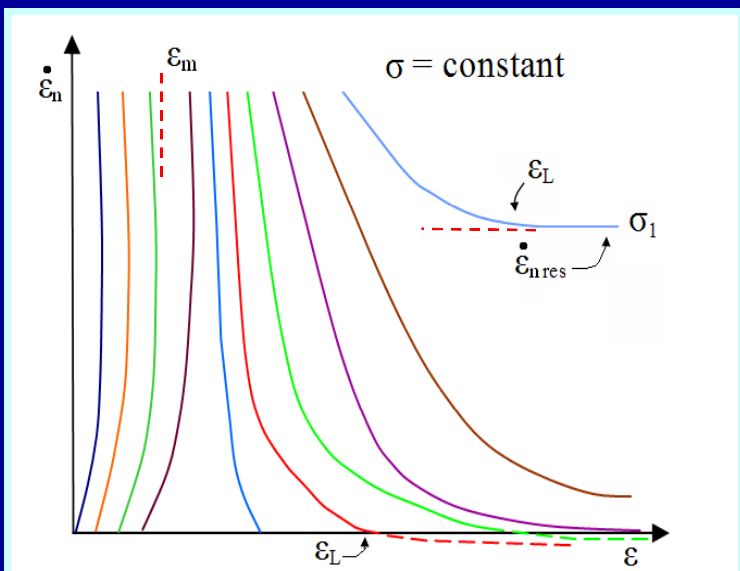
Conceptual cyclic strain-rate controlled cyclic loading response for a series of cyclic loading tests (cyclic envelope shown for clarity)

$$\dot{\varepsilon}_n = \dot{\varepsilon}_{n01} \times (\varepsilon - \varepsilon_m)^{-\beta_{n1}} + \dot{\varepsilon}_{n\,res}$$

$\dot{\varepsilon}_{n01}$ - Reference Strain Rate

β_{n1} - Cyclic Creep Index

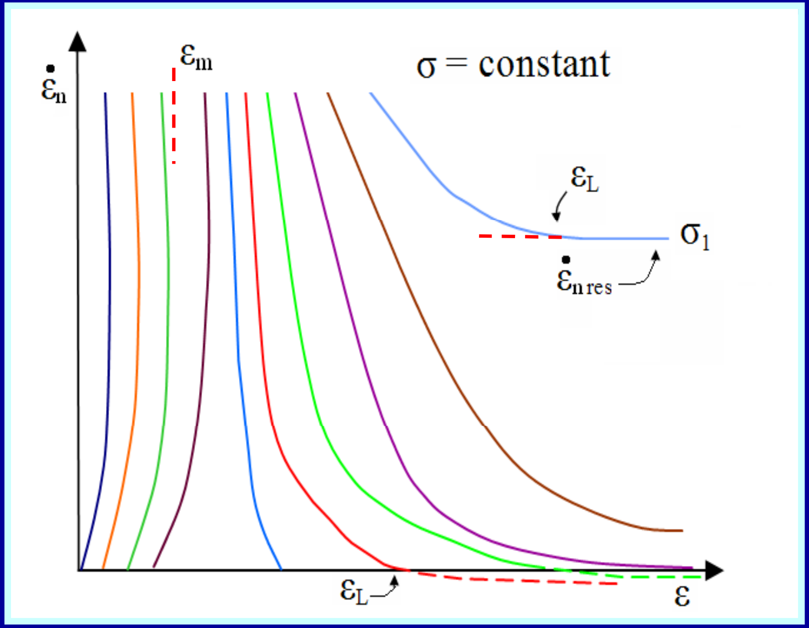
$\dot{\varepsilon}_{n\,res}$ - Residual Strain Rate

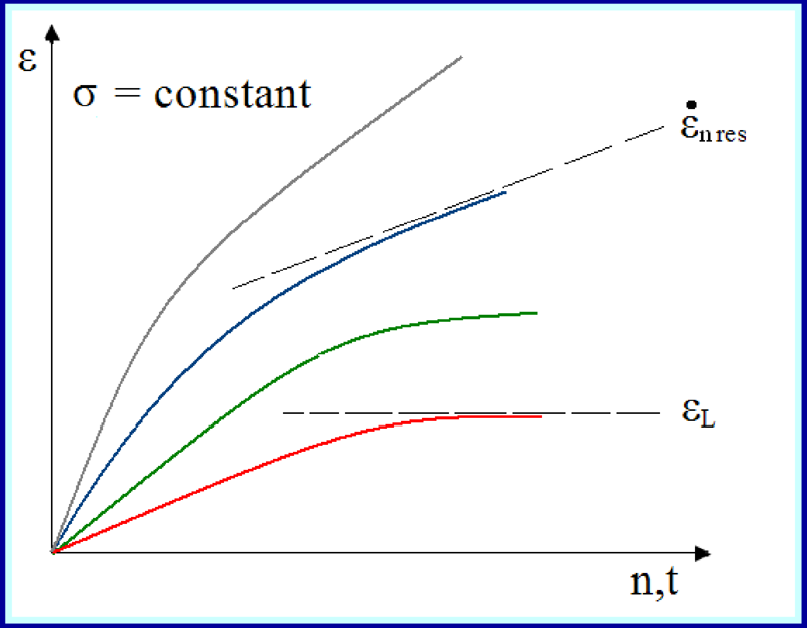


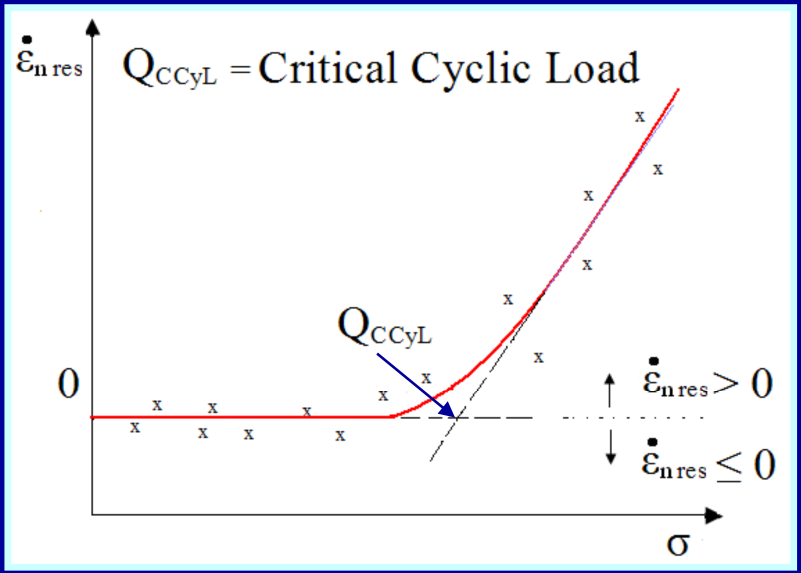
Conceptual cyclic strain rate-strain curves (constant stress levels)

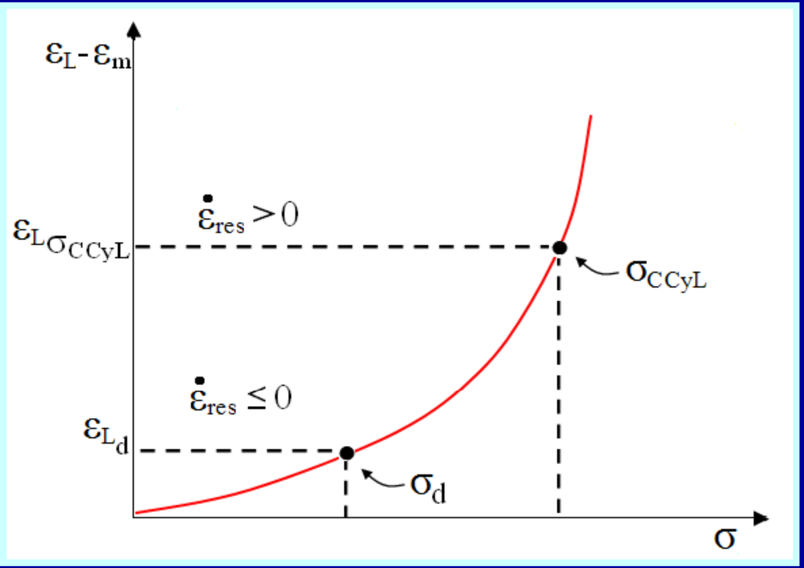
$$(\varepsilon_L - \varepsilon_m) = \left(\frac{\dot{\varepsilon}_{n\,res}}{\dot{\varepsilon}_{n01}} \right)^{-1/\beta_{n1}}$$

Model Application to Establish the Critical Cyclic Load and Design Load for Allowable Displacement

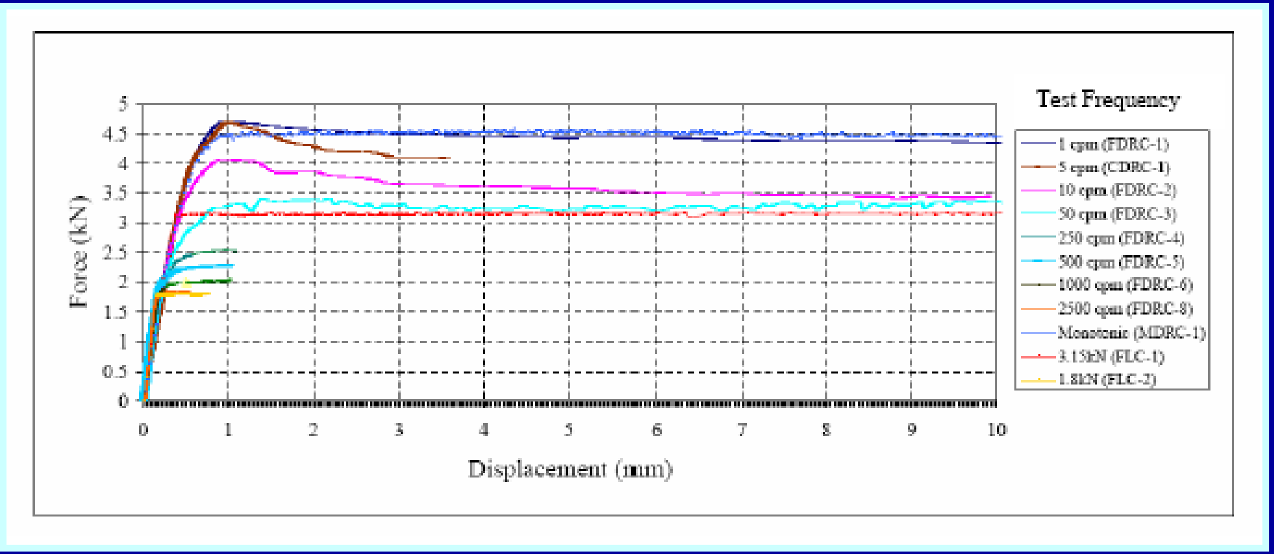




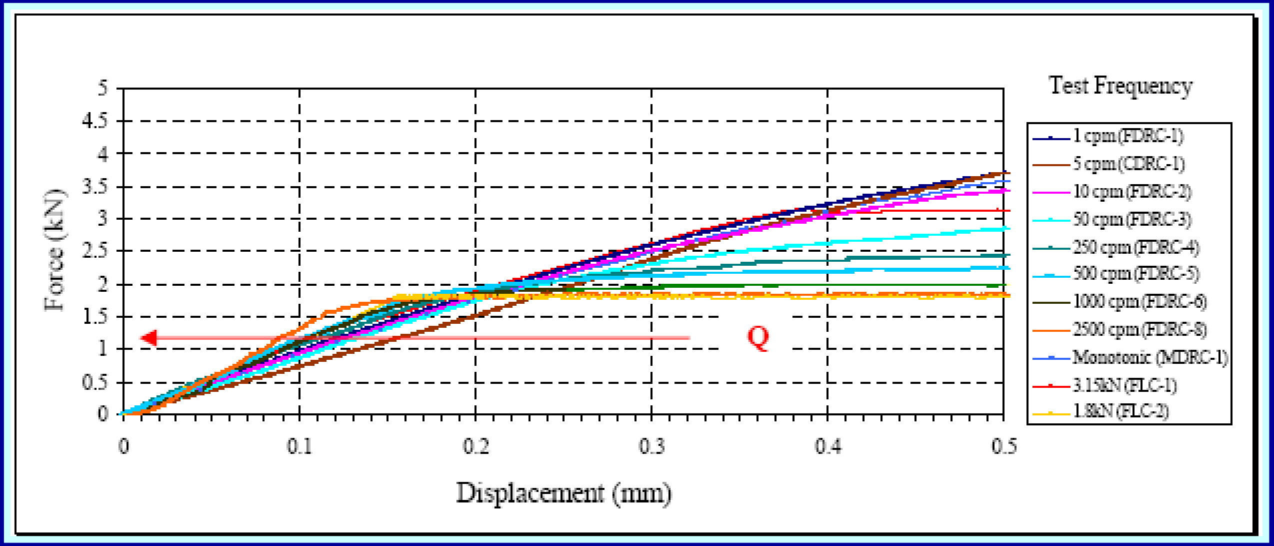




Experimental Evaluation of Testing Procedure & Interpretation Model for Cyclic Loading : (Cyclic Displacement Rate)

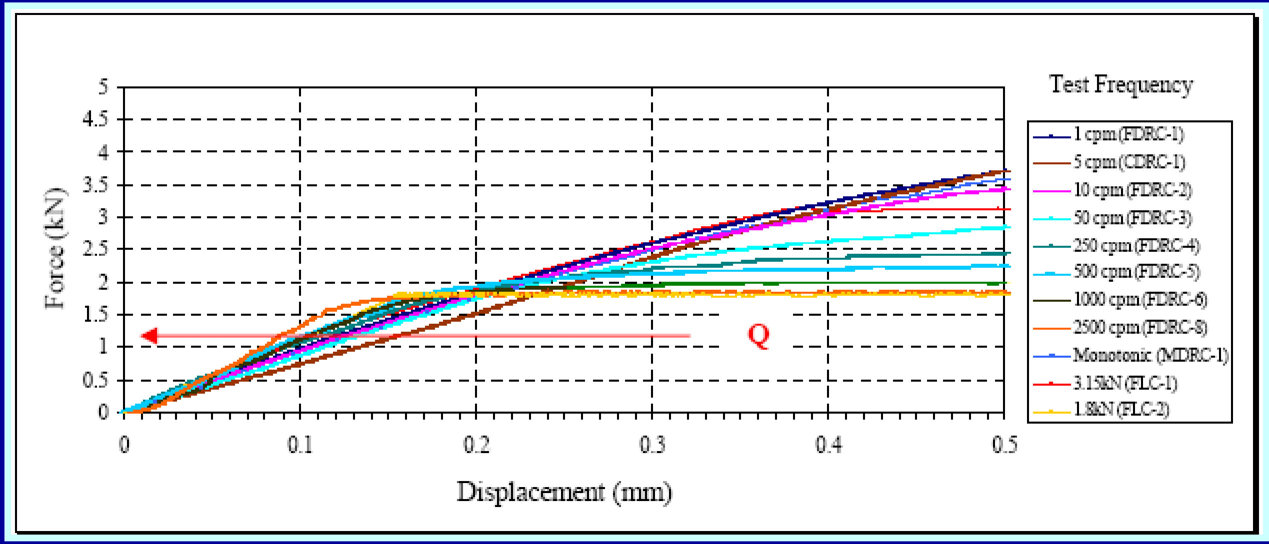


Force vs. displacement

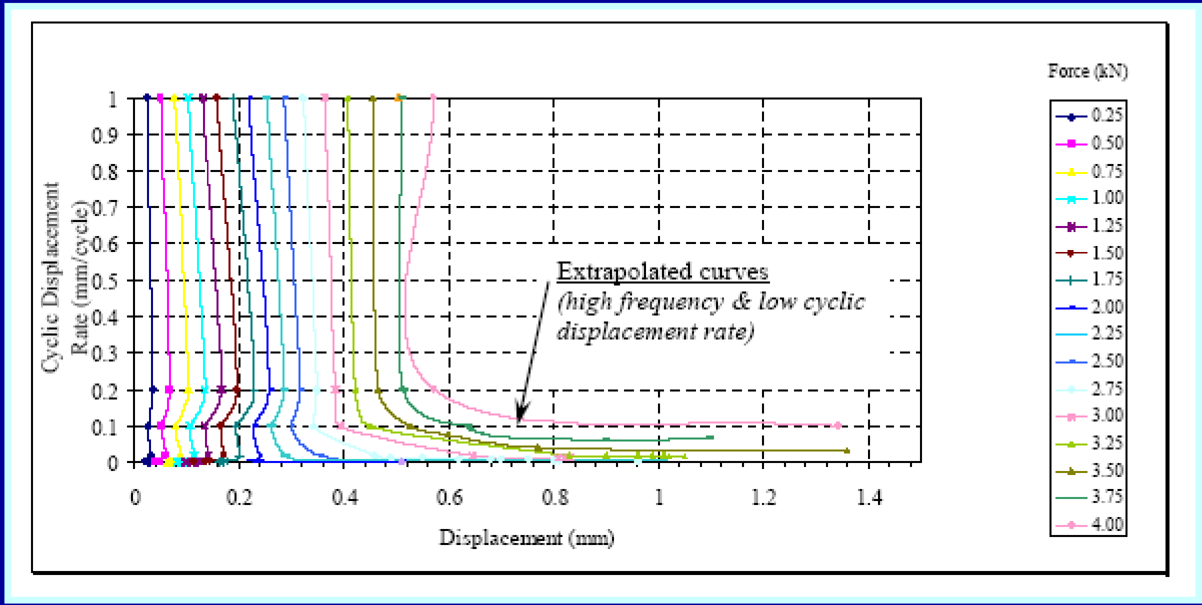


Force vs. displacement (region of initial displacement)

Experimental Evaluation of Testing Procedure & Interpretation Model for Cyclic Loading : (Cyclic Displacement Rate)

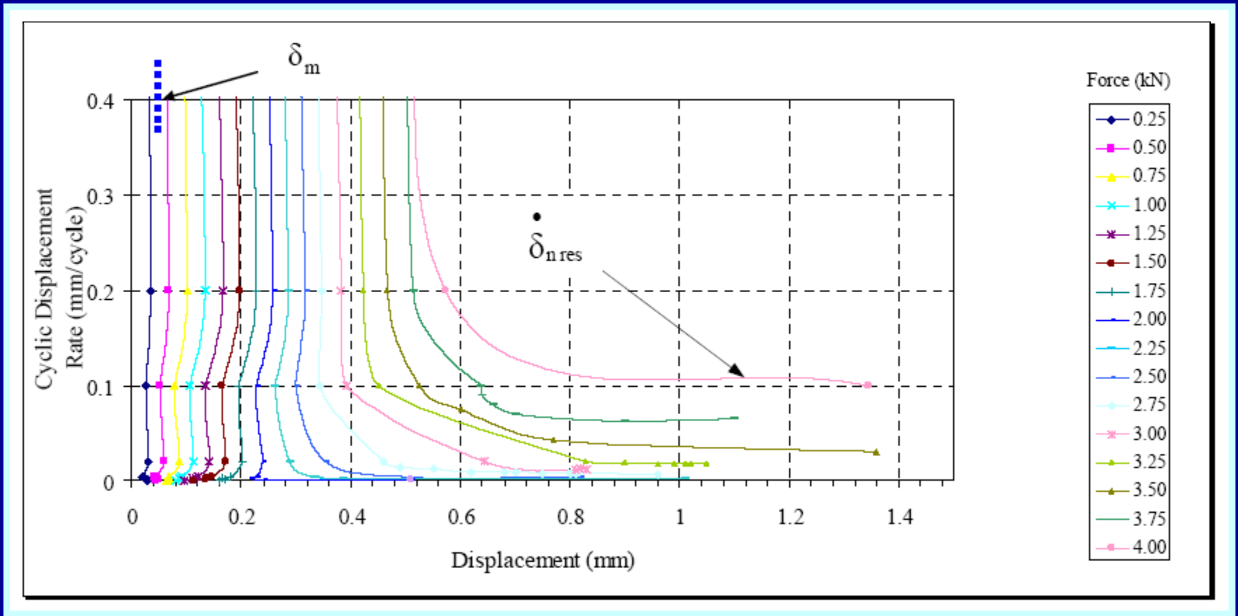


Force vs. displacement rate (region of initial displacement)

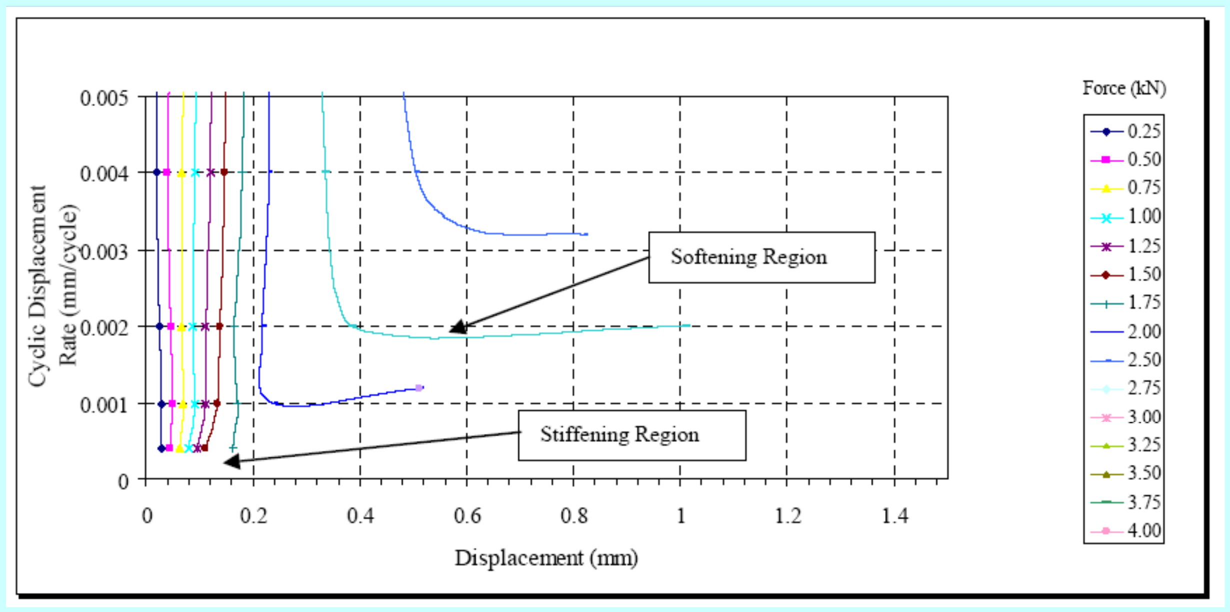


Cyclic displacement rate vs. displacement (constant levels of force)

Experimental Evaluation of Testing Procedure & Interpretation Model for Cyclic Loading : (Cyclic Displacement Rate)

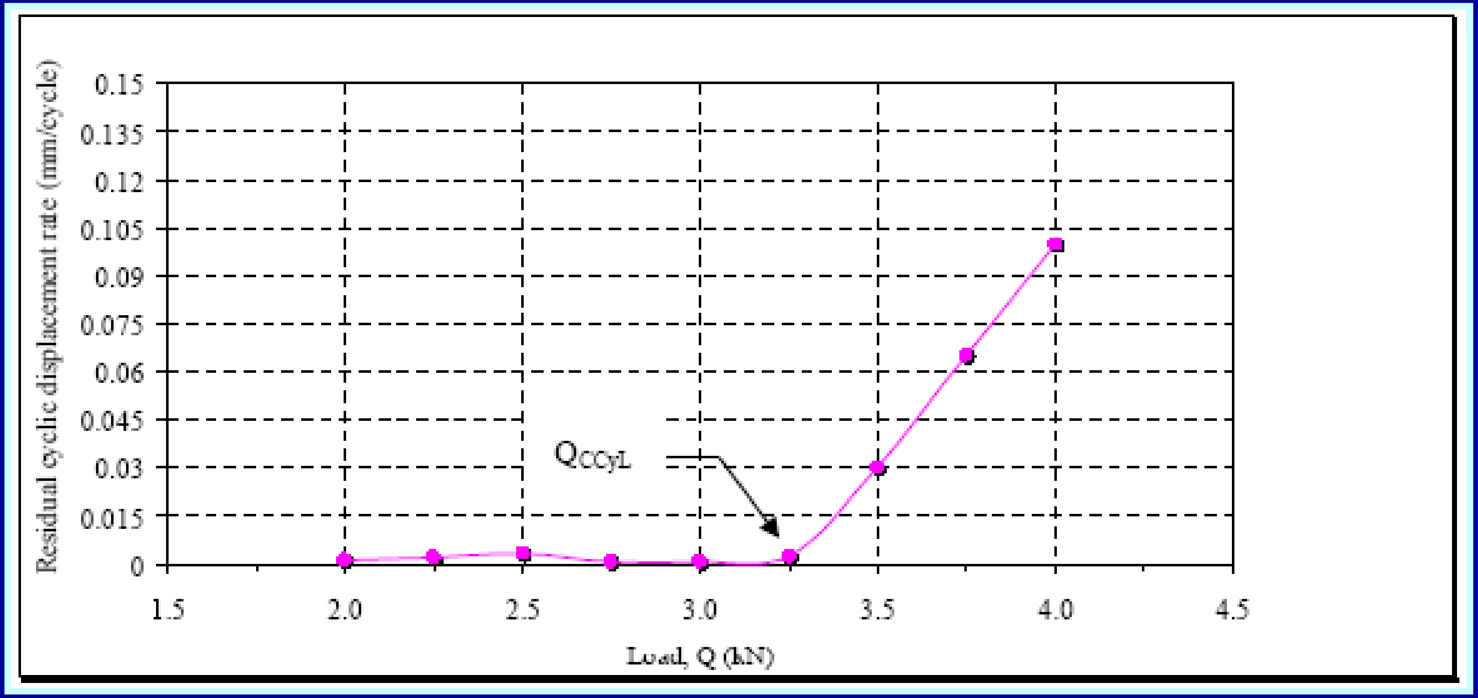


Cyclic displacement rate vs. displacement – effect of frequency



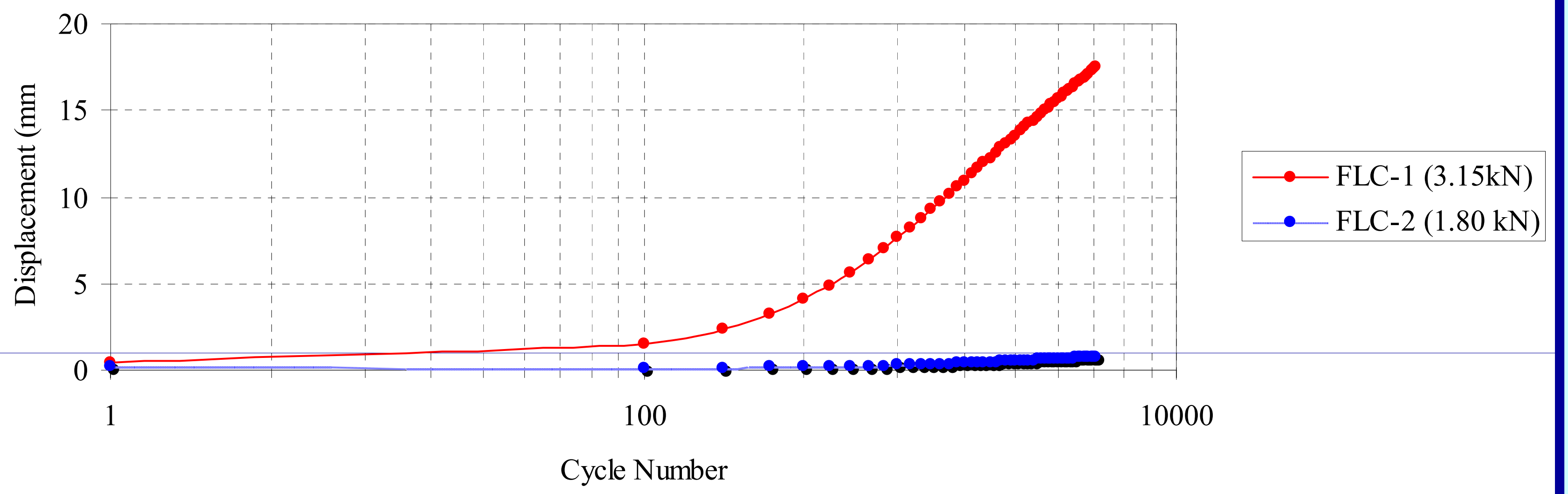
Cyclic displacement rate vs. displacement – regions of cyclic softening/stiffening

Experimental Evaluation of Testing Procedure & Interpretation Model for Cyclic Loading (Cyclic Displacement Rate): Critical Cyclic Load



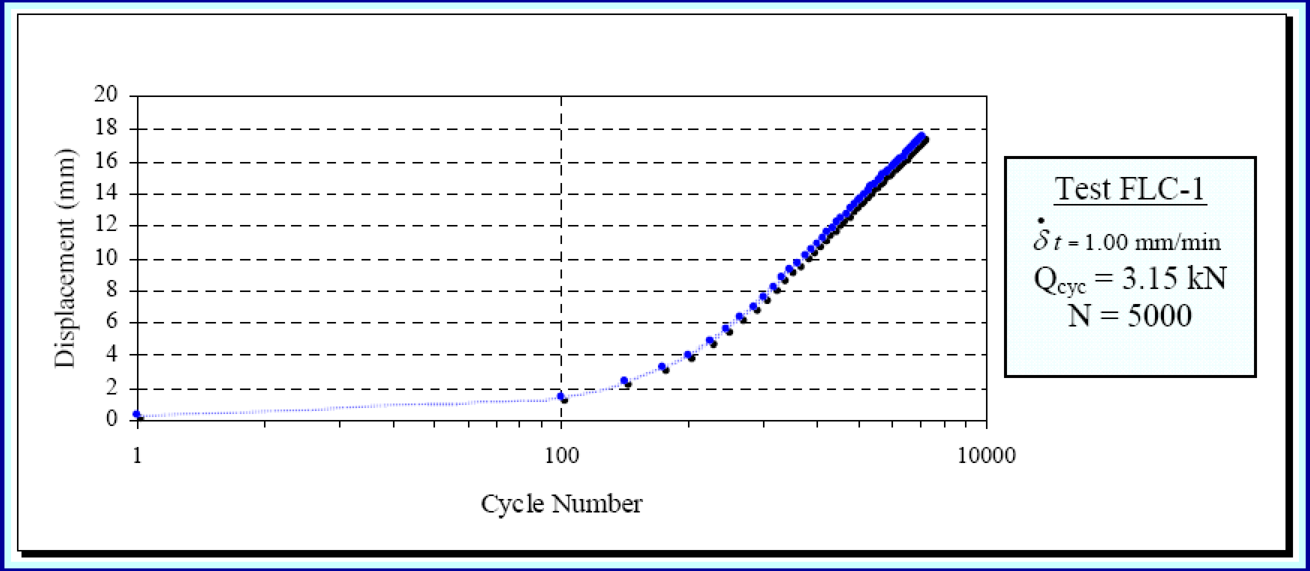
Residual cyclic displacement rate vs. load

Experimental Evaluation of Testing Procedure & Interpretation Model for Cyclic Loading : Load-Controlled Cyclic Loading Tests

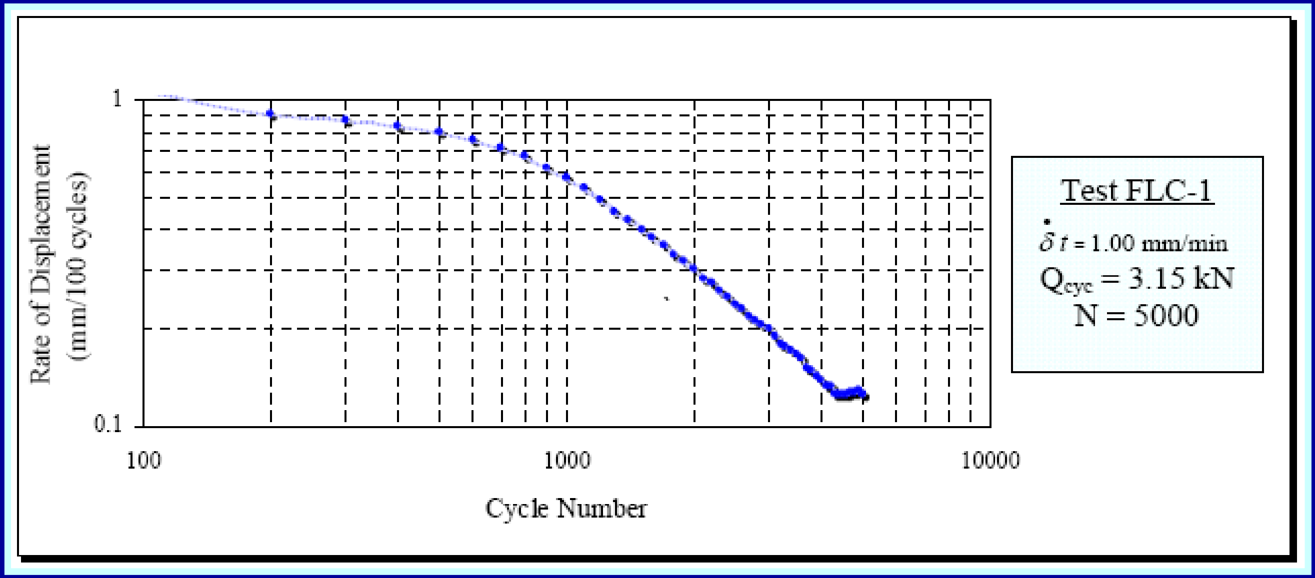


Displacement vs. Cycle Number

Experimental Evaluation of Testing Procedure & Interpretation Model for Cyclic Loading : Load-Controlled Cyclic Loading Tests

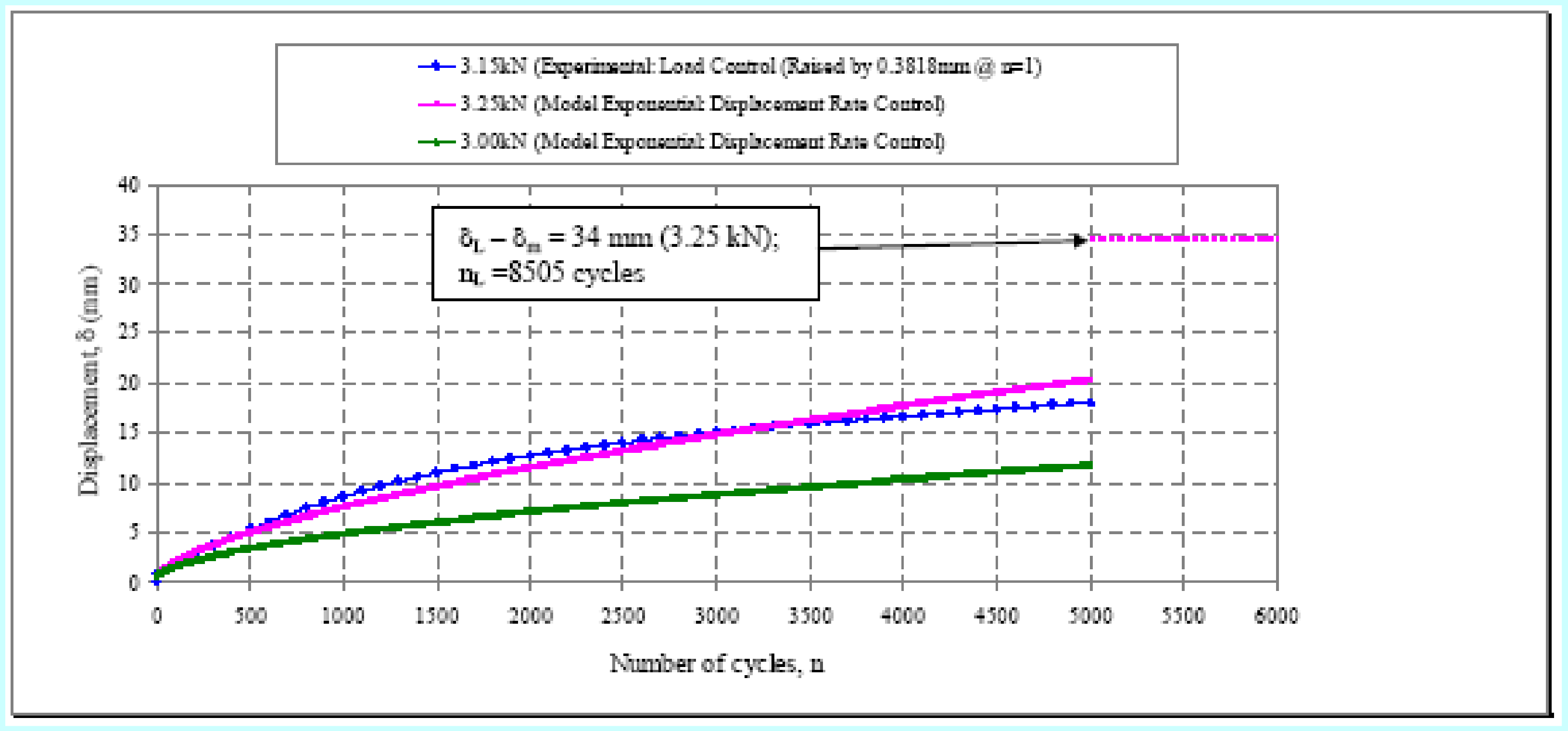


Total displacement rate vs. number of cycles



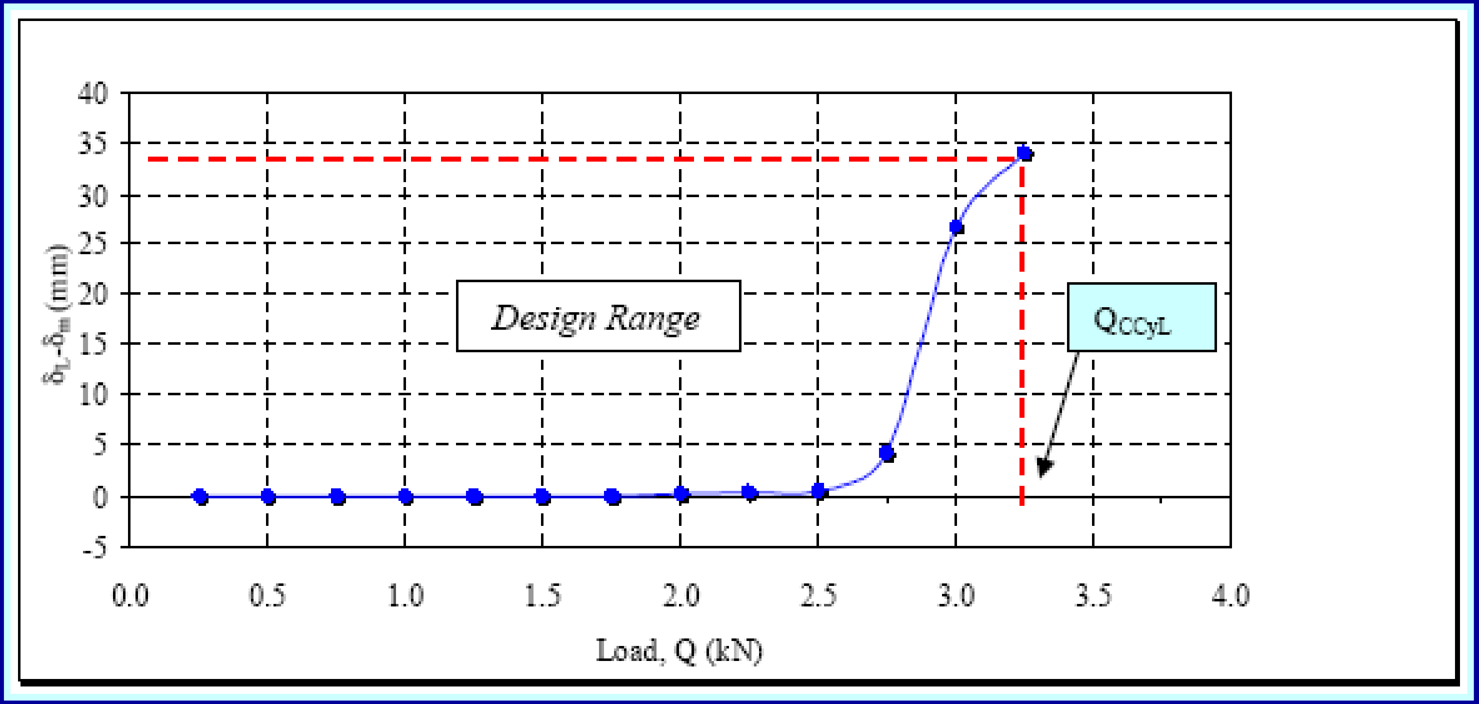
Rate of displacement vs. number of cycles (100's of cycles)

Experimental Evaluation of Testing Procedure & Interpretation Model for Cyclic Loading (Cyclic Displacement Rate): Prediction of Displacement



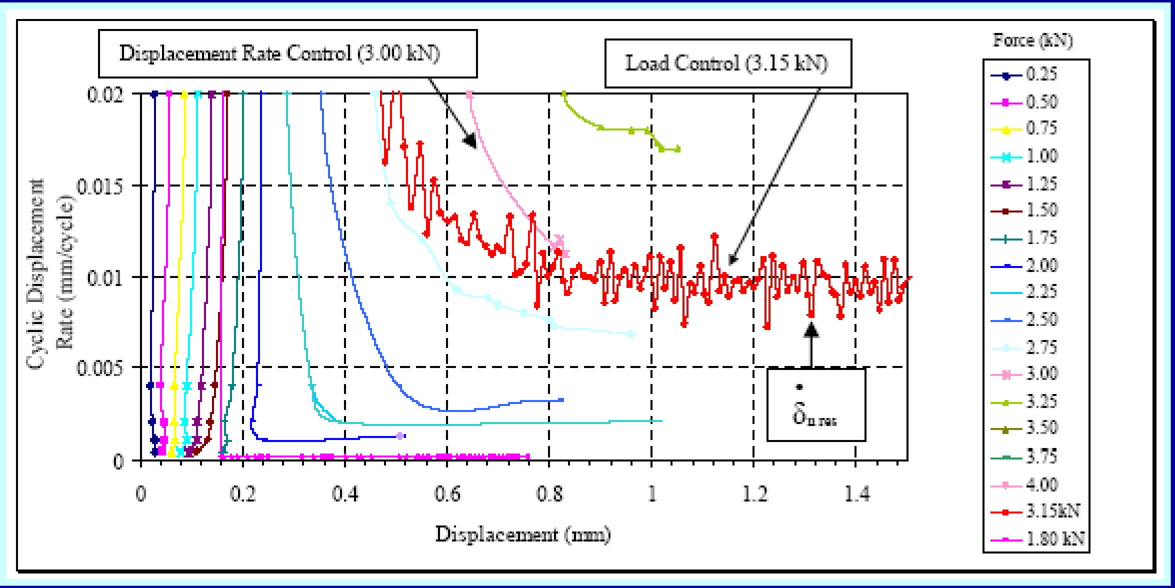
Displacement vs. number of cycles for load level $Q \approx Q_{CCyL}$

Experimental Evaluation of Testing Procedure & Interpretation Model for Cyclic Loading (Cyclic Displacement Rate): Critical Cyclic Load

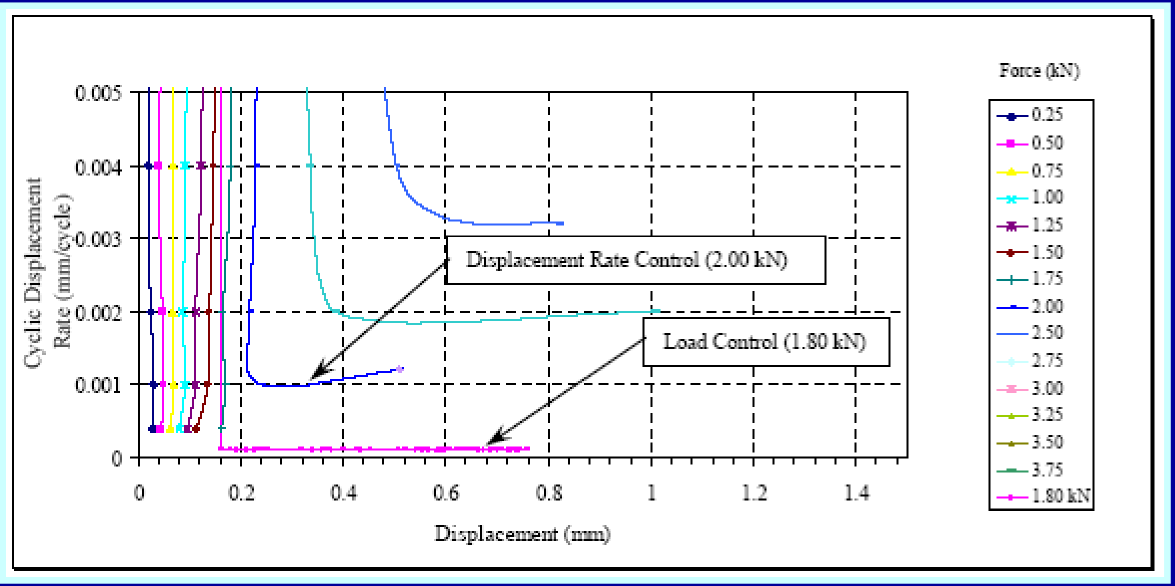


Limit cyclic displacement vs. load

Experimental Evaluation of Testing Procedure & Interpretation Model for Cyclic Loading (Cyclic Displacement Rate)



Cyclic displacement rate versus displacement (constant levels of load) for load-controlled and displacement-rate controlled tests (Q = 3.15 kN)



Cyclic displacement rate versus displacement (constant levels of load) for load-controlled and displacement-rate controlled tests (Q = 1.80 kN)

Conclusions

- **Experimental Model Evaluation** illustrates that long-term behavior of strain-rate dependent and frequency dependent materials and mechanisms such as soil-pile interaction can be predicted using the short-term strain rate controlled cyclic model pile test results.

- **For design practice,** the proposed short-term testing procedure and interpretation model provide reliable methodology to establish for both strain-rate and frequency-dependent materials :
  - Critical creep load
  - Critical cyclic load
  - Long-term cyclic strains or displacement under any loading level and frequencies
  - Design load for allowable long-term cyclic strain or displacement.

- **For research purposes,** the proposed short-term testing procedure provides a most efficient methodology to parametrically investigate the effect of material properties and loading characteristics on the long-term performance of geosystems, such as micropiles, piles and ground anchors, soil nails, etc. and their soil -inclusion interaction mechanisms under long-term cyclic loading.

- **Further Research and Impact on Engineering Practice.** Existing pile load testing equipment could be modified to conduct full-scale field loading tests using the suggested testing protocol. If successful, testing standards could be developed which could lead to adopting the proposed cyclic strain testing procedure and strain rate controlled cyclic strain model as a base line for industry pile testing and design standards.

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DBM Construction
Geosystems LP
Hayward Baker, Inc.
Ischebeck
Isherwood Associates
Layne GeoConstruction
Moretrench American Corp.
Nicholson Construction
TEI Rock Drills